

2020-08

Indoor air quality (IAQ) in naturally-ventilated primary schools in the UK: Occupant-related factors

Korsavi, Sepideh Sadat

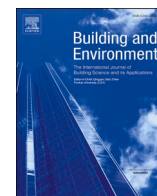
<http://hdl.handle.net/10026.1/18018>

10.1016/j.buildenv.2020.106992

Building and Environment

Elsevier BV

All content in PEARL is protected by copyright law. Author manuscripts are made available in accordance with publisher policies. Please cite only the published version using the details provided on the item record or document. In the absence of an open licence (e.g. Creative Commons), permissions for further reuse of content should be sought from the publisher or author.



Indoor air quality (IAQ) in naturally-ventilated primary schools in the UK: Occupant-related factors

Sepideh Sadat Korsavi^{a,*}, Azadeh Montazami^a, Dejan Mumovic^b

^a Centre for the Built and Natural Environment (BNE), Faculty of Engineering, Environment and Computing, Coventry University, 3 Gulson Road, CV1 2JH, UK

^b Institute for Environmental Design and Engineering, University College London (UCL), Central House, 14 Upper Woburn Place, London, WC1H 0NN, UK

ARTICLE INFO

Keywords:

Indoor air quality (IAQ)
CO₂ levels
Occupants
Adaptive behaviours
Occupancy density (OD)
Primary schools

ABSTRACT

Indoor Air Quality (IAQ) is affected by *Context, Occupant and Building* (COB) related factors. This paper evaluates IAQ as a function of occupant-related factors including occupants' Adaptive Behaviours (ABs), occupancy patterns, occupant's CO₂ generation rates and occupancy density. This study observed occupant-related factors of 805 children in 29 naturally-ventilated (NV) classrooms in UK primary schools during Non-Heating and Heating seasons.

Occupant-related factors affecting IAQ include occupants' adaptive behaviours, occupancy patterns, occupants' CO₂ generation rate and occupancy densities. Results of this study suggest that a classroom with high potentials for natural ventilation does not necessarily provide adequate IAQ, however, occupants' good practice of ABs is also required. Average occupancy densities to have CO₂ levels of 1000 ± 50 ppm are suggested to be $2.3 \pm 0.05 \text{ m}^2/\text{p}$ and $7.6 \pm 0.25 \text{ m}^3/\text{p}$. These values correspond to the classroom area of $62.1 \pm 1.35 \text{ m}^2$ and volume of $205.2 \pm 6.75 \text{ m}^3$ with a height of 3.3 m. Mean CO₂ level is maintained below 900 ppm when all occupant-related factors are in the favour of IAQ, however, it exceeds 1300 ppm when none of the occupant-related factors are in favour of IAQ.

It is shown that 17% of CO₂ variations are explained by open area (m^2), 14% by occupants' generation rates (cm^3/s) and 11% by occupancy density (m^3/p). IAQ is mostly affected by occupants' adaptive behaviours than other occupant-related factors in naturally-ventilated classrooms.

1. Introduction

Children spend almost 12% of their life inside classrooms, that is more time than in any other building except their home [1,2]. School and government authorities should ensure that appropriate indoor air quality (IAQ) is maintained for children [3]. IAQ in schools is recognized as one of the most important factors affecting students' health [4–9] and academic performance [10–13]. IAQ in classrooms is mainly assessed by CO₂ levels [14–18], especially in buildings where people, exhaled air or bio-effluents are the main pollution sources [19]. Authors have previously suggested [20] that the main factors influencing IAQ in buildings fall into three categories of *Context, Occupant and Building* (COB). 1) *Contextual* factors on the macro level such as climatic conditions [21] and season [22–24], or the micro level such as regional temperature [25] and draughts from windows [26], 2) *Building-related* factors such as airtightness [27,28], schools' location, classrooms and windows' design [21], type of ventilation, ventilation rate [27], CO₂ exhalation rate and

room volume [29], 3) *Occupant-related* factors such as occupants' behaviour [26,27], maintenance and operation of systems, operating schedule [27], number of occupants [28,30], activity levels, amount of time spent in the room, previous room's occupancy [23], occupants' age and diet [9,25], and individual's thermal comfort [5].

It is important to focus on occupant-related factors affecting IAQ in primary schools for four main reasons; 1) Children have physical and physiological differences with adults [31–35], which makes them more vulnerable and less resistant than adults to health risks from environmental hazards [36–41]. Physically, children have a smaller body surface area [42], have narrower airways [43,44], their organs, tissues and immune system are not fully developed [45] and their body's defence against infection is limited [44]. Children breathe in more air (approximately 50% more) into their developing lungs relative to their body weight [46,47]. Physiologically, children have higher metabolic and respiration rates [48] which results in children producing heat at a rate of 85% of that for adults [49,50]. 2) Due to above-mentioned differences

* Corresponding author.

E-mail addresses: korsavis@uni.coventry.ac.uk (S.S. Korsavi), azadeh.montazami@coventry.ac.uk (A. Montazami), d.mumovic@ucl.ac.uk (D. Mumovic).

<https://doi.org/10.1016/j.buildenv.2020.106992>

Received 8 March 2020; Received in revised form 15 May 2020; Accepted 19 May 2020

Available online 31 May 2020

0360-1323/© 2020 Elsevier Ltd. All rights reserved.

and also teachers' role in controlling classrooms [51,52], children's environmental adaptive behaviours are more limited than that for adults [53–55]. The impact of poor IAQ on children is exacerbated because they usually do not complain about it [55,56]. 3) Classrooms are more crowded than other workplaces [45,57] and occupancy density of classrooms is about four times higher than that of office buildings [58]. Therefore, CO₂ exhalation rate can be higher in schools. 4) Children's perception of IAQ can negatively be affected by external factors, such as type of their work [45,55] and their stress level [59]. Children's work in schools is almost always new to them, while adults frequently perform routine tasks [55]. Thus, the effect of environmental conditions on schoolwork performance by children is larger than that on office-work performance by adults [60].

Healthy IAQ is vital for the health of children as they are more sensitive towards indoor air pollutants. Hence, the effect of occupant-related factors on IAQ is remarkable in the context of primary school buildings, especially considering potential unpredictability of occupant-related factors. This paper aims to provide a detailed analysis of IAQ as a function of occupant-related factors during heating and non-heating seasons to deliver healthier classrooms for the next generation of children.

2. Methodology

The main steps carried out in this methodology are 1. Sampling climate, building, windows' design and occupants, 2. Acquiring data on adaptive behaviours, occupancy patterns, and environmental measurements. 3. Calculating occupants' CO₂ emission rate 4. Reviewing Standards, 5. Overviewing recorded data.

2.1. Sample selection

In this study, samples were selected with specific attention to the climate in which buildings were located, buildings and their neighbourhood, windows within the buildings and buildings' occupants.

2.1.1. Climate

The study was carried out in Coventry, West Midland, with a mild climate according to Koppen classification [61] from mid-July 2017 until the end of May 2018 to represent all climatic conditions. Schools were selected in the *mild* climate of the UK because mild or temperate climates can provide opportunities for buildings' natural ventilation [62–65] and can reduce the biased impact of extreme climates on window operation in NV buildings.

2.1.2. Buildings

To study the effect of occupant-related factors, especially adaptive behaviours on IAQ, selected schools met five criteria. 1) Selected schools in this study are naturally ventilated since the main source of ventilation in most UK schools is windows. Furthermore, variations in temperature, humidity and pollutants from mechanical ventilation and air-conditioning systems [66] can limit our understating about IAQ in buildings and its relation with occupants. 2) Buildings were selected in quiet areas to not restrict window operation due to high background noise level, as supported in Ref. [67,68]. 3) Buildings were selected in low-polluted areas to not restrict window operation due to high pollution level, as supported in Ref. [15,16,68]. 4) Buildings were selected with different architectural features as different buildings provide different potentials for practising adaptive behaviours (ABs), Table 1. 5) Schools were selected among both renovated and existing buildings

Table 1

An overview of the architectural features of schools and classrooms.

General		Classroom		Window Design			W Operation			NO ⁵	Density ⁶		AB ⁷
Mode	No.	Area	Vo ¹	WA ²	NW ³	W Type	Ventilation	MW ⁴			M ² / p	M ³ / p	
Non-heating	1.1	60	192	8	8	Top-hung outward openings at 2 levels	Single-sided windows at 2 level + louvre opening	1	Manually	25	2.4	7.7	H
	1.2	60		8	8			1	Manually	25	2.4	7.7	H
	1.3	60		8	8			1	Manually	25	2.4	7.7	H
	1.4	60		8	8			1	Manually	28	2.1	6.9	H
	2.6	60	192	8	8	Top-hung outward openings at 2 levels	Single-sided windows at 2 level + louvre openings	1	Manually	29	2.1	6.6	H
	2.7	60		8	8			1	Manually	26	2.3	7.4	H
	2.8	60		8	8			1	Manually	30	2.0	6.4	H
	2.9	60		8	8			1	Manually	28	2.1	6.9	H
	Heating	3.10	65	227	2	5	Top-hung outward	Single-sided	1.7	Manually	25	2.6	9.1
3.11		70	245	2.2	6	Double-sided		1.6	Manually	28	2.5	8.8	L
3.12		60	192	2.5	5	Single-sided		2.6	With handle	25	2.4	7.7	L
4.13		50	130	0.5	2	Top-hung outward	Single-sided	1.8	Manually	27	1.9	4.8	L
4.14		60	156	0.5	2			1.8	Manually	26	2.3	6.0	L
4.15		50	175	0	0		–	No opening	–	No window	29	1.7	6.0
5.16		55	137	5.7	8	Top-hung openings at 2 levels	Single-sided at two levels	0.5	Manually	30	1.8	4.6	H
5.18		55		5.7	8			0.5	Manually	27	2.0	5.1	H
5.20		55		5.7	8			0.5	Manually	32	1.7	4.3	H
6.21		60	168	1.8	4	Top-hung outward opening	Single-sided windows + Louvre openings	2.3	Remote-control	29	2.1	5.8	L
6.22		60		1.8	4			2.3		28	2.1	6.0	L
6.23		60		1.8	4			2.3		30	2.0	5.6	L
6.24		60		1.8	4			2.3		29	2.1	5.8	L
6.25		60		1.8	4			2.3		30	2.0	5.6	L
Non-heating		7.26	70	252	3.9	6	Top-hung outward opening	Double-sided	2.7	With handle	29	2.4	8.7
	7.27	55	137	3.3	3	Single-sided		1.65	Manually	27	2.0	5.1	H
	7.28	55	137	5.4	6	Double-sided		1.6	Manually	30	1.8	4.6	H
	8.29	60	150	2.2	4	Top-hung outward opening	Single-sided	1.4	Manually	28	2.1	5.4	L
	8.30	60	150	2.2	4			1.4	Manually	29	2.1	5.2	L
	8.31	55	137	2.2	4			1.4	Manually	24	2.3	5.7	L
	8.32	55	137	2.2	4			1.4	Manually	26	2.1	5.3	L

1 = Volume(m³)- 2 = Window Area (m²)- 3 = Number of Windows- 4 = Minimum Height of window sill (m)- 5 = Number of Occupants- 6 = Occupant Density (m²/number of students and m³/number of students)- 7 = Potentials for practice of AB.

because they should comply with different IAQ standard. Schools 1, 2 and 6 (13 classrooms) are among renovated schools and the rest (16 classrooms) are among existing buildings. In total, 29 naturally ventilated classrooms in eight primary schools were selected and studied during non-heating (NH) and heating (H) seasons, Table 1. Further details on the selection of the school buildings can be found in an earlier study by authors [52].

2.1.3. Windows

To study how window design affects occupants' Adaptive Behaviour (AB), classrooms are classified into two groups that provide high or low potentials for the practice of ABs based on a comprehensive literature review on window design.

Windows' design: High and low-level openings by reducing draughts in the occupied zone and directing the airflow above the occupied head height zone can reduce CO₂ concentrations without discomforting occupants [15]. It is shown that large openings can be used for still summer days and small high-level openings can be used for winter days to avoid overheating [50,69]. Windows at different levels (high and low-level openings) and sizes (small and large) can provide IAQ [15,20,50,69–71] during both heating and non-heating seasons. Therefore, classrooms with windows at different levels and sizes can potentially increase occupants' practice of ABs. Columns 5–9 in Table 1 (under window design section) show windows' area, number of windows, windows' type, ventilation type and a minimum height of operable windows, respectively.

Windows' operation: Windows' operation method affects occupants' practice of ABs; it is shown that manual operation of windows helps to improve IAQ significantly [20,30,40,72,73] and makes people feel more comfortable in manually-controlled buildings [20]. Based on children's physiology, safe windows designed at lower heights are more accessible for children's window operation [20,52]. Therefore, classrooms that provide windows at accessible heights with manual and easy operation for children can potentially increase occupants' practice of ABs. Windows operated with a remote control or a handle suggest lower potentials for practice of ABs. Column 10 in Table 1 shows windows' type of operation. Classrooms that provide both of above criteria are classified as classrooms with high potentials for practice of ABs. The last column in Table 1 shows that 13 classrooms provide high potentials for practice of ABs and 16 classrooms provide low potentials for practice of ABs.

Fig. 1 shows a classroom with single-sided double openings at two different sizes and levels that are operated manually alongside the length of the classrooms (school 5). Fig. 2 shows a classroom with 2 small windows at the height of 1.8 m located at the end of the classroom (school 4).

2.1.4. Occupants

Among primary school students, children in their late middle childhood (9–11 YO) compared to their peers in early middle childhood (6–9 YO) were selected as the main respondents of this study. Children

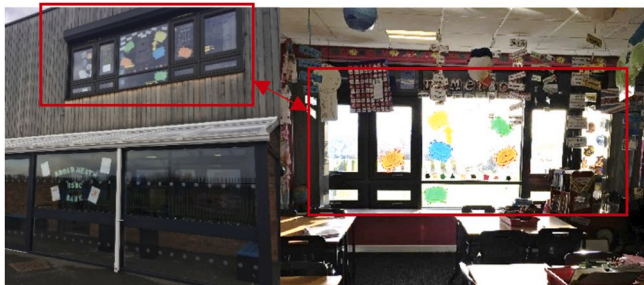


Fig. 1. Classroom providing high potentials for practice of ABs (indoor and outdoor view).



Fig. 2. Classroom providing low potentials for practice of ABs (indoor and outdoor view).

in late middle childhood compared to their peers have a better understanding of their environment [52] and have higher heights according to UK-World Health Organisation growth charts [42] which let them be more engaged in environmental adaptive behaviours. Furthermore, older children are allowed to move around during classroom breaks and operate controls, whereas younger children are kept under stricter supervision inside the classrooms [74].

2.2. Data acquisition

The overview of behavioural studies shows that they mostly use transverse method to collect data [75–83], therefore, the study applies the transverse method. Hence, data acquisition and observations were carried out in 29 different classrooms on 29 distinct days throughout one year. To increase the validity of the study and reduce bias, the number of studied classrooms is similar during both seasons, 15 classrooms during non-heating and 14 classrooms during heating seasons. Table 1 shows the number of studied classrooms, the season at which each classroom was studied and the number of observed children in each classroom.

An observation form that was developed and validated in an earlier study by authors [84] is used to obtain information on architectural features, occupancy patterns and controls' operation, Table 2. Observations were conducted to have an in-depth understanding of factors affecting IAQ, as applied in another study [85]. Occupancy patterns and window operations are observed at 10-min intervals.

Schools' occupied period is divided into three categories, teaching, non-teaching and total period. In this study, teaching period accounts for 75.4% of the times and non-teaching period, consisting of lunch breaks (11.3%), assembly (6.9%), short breaks (5.4%) and Physical Education (PE) (1%), accounts for the rest 24.6% of the times. The total period of occupancy (09:00–15:30) consists of both teaching and non-teaching period.

2.2.1. Environmental measurements

Environmental variables affecting occupants and their adaptive behaviours were recorded at 5-min intervals by multi-functional SWEMA equipment, standalone data loggers and CO₂ meter (TGE-0011, accuracy: $\pm 50 + 2\%$ of the reading) at a height of 1.1 m as recommended by ISO 7726 [86]. Specifications of the measuring equipment are shown in Table 3.

The instruments were usually set up in the classrooms before children's arrival in the morning and continued recording until the end of the school day (08:50–15:30). Time-lapse cameras were installed inside the classrooms to record occupants' adaptive behaviours on blinds and doors at 5-min intervals.

2.3. Carbon dioxide (CO₂) generation (G)

CO₂ generation (G) is calculated based on children's age, metabolic

Table 2

Questions on architectural features, occupancy patterns and adaptive behaviours taken from questionnaires developed by authors [84].

Variables		Questions and Responses	
Observation at 10-min interval	Occupancy Patterns	No. Students in the classroom? Type of subject? (<input type="checkbox"/> math, <input type="checkbox"/> English, <input type="checkbox"/> art, ...)	
		Type of activity? <input type="checkbox"/> Seated, Reading and writing, <input type="checkbox"/> Standing and tidying, singing, <input type="checkbox"/> dancing or performing	
		Occupancy pattern in the classroom? <input type="checkbox"/> Occupied, <input type="checkbox"/> not occupied, <input type="checkbox"/> Left for break, <input type="checkbox"/> left for PE, <input type="checkbox"/> left for lunch, <input type="checkbox"/> left for assembly, <input type="checkbox"/> left for home	
	Windows operation	Total open area (m ²)? ... Total number of window adjustments? ...	
	Classrooms' architectural features	Classroom area (m ²)? ... Total area of operable windows (m ²)? ...	
Type of window operation? ... (<input type="checkbox"/> manual, <input type="checkbox"/> manual with a handle, <input type="checkbox"/> automatic, <input type="checkbox"/> remotely controlled)			
Type of window opening? ... (<input type="checkbox"/> Top hung, <input type="checkbox"/> side hung, <input type="checkbox"/> horizontal slider, <input type="checkbox"/> hopper, <input type="checkbox"/> awning, <input type="checkbox"/> casement)			
Depth to Height Ratio? ... Openings area to classroom area? ... Min Height of operable windows? ...			
Type and number of doors? (<input type="checkbox"/> connecting door between classes, <input type="checkbox"/> internal door, <input type="checkbox"/> external door)			

Table 3

Specifications of the measuring equipment shown in an earlier study by authors [84].

Probe	Variables	Meas. Range	Resolution
SWEMA	Humidity and air temperature	0 to 100 %RH, −40 to +60 °C	0.1% RH 0.1 °C
	Air velocity and, Air temperature	0.05–3.0 m/s at 15–30 °C, +10 to +40 °C	1.1 m/s 0.1 °C
	Radiant temperature (Ø globe: approx.150 mm)	0 to +50 °C	0.1 °C
Data Logger	Temperature	−35 to +80 °C	0.1 °C
TGE-0011	Humidity	0 to 100 %RH	0.5% RH
	CO ₂	0–5000 ppm	1 ppm

rate, body surface area and room temperature. CO₂ generation for an average child is given in Equation (1) [26]:

$$G = \frac{-0.94(A - 5) + 52.3}{40} k \quad (1)$$

Where

$$k = 0.148\alpha m \frac{273 + tr}{273} \quad (2)$$

G (kg/s) is CO₂ generation

A (years) is children's age

m (W/m²) is the metabolic rate

α (m²) is body surface area and

t_r(°C) is room temperature

Body surface area is calculated from Dubois equation (3) [26] when w = weight (kg) and h = height (m), are known [26].

$$a = 0.202w^{0.425}h^{0.725} \quad (3)$$

Children's height and weight were derived from UK-World Health Organisation growth charts (average weight = 32 Kg and average height = 1.38 m) [42]. Average body surface area of 9–11 years old children was found 1.1 m² [42].

Metabolic Equivalent of Task (MET) is the ratio of the working metabolic rate to the metabolic rate at resting condition [41]. MET equals the energy produced per unit surface area of an average person (1.8 m²) seated at rest [58], where 1 MET = 58.2 W m^{−2} for seated relaxed activities [58,86]. MET expresses physical activity of humans and varies with type of activity [86]. Metabolic rate of children can be modified by considering 0.85 value to metabolic rate of adults [87,88] because children produce heat at a rate of 85% of that for adults [15,49,50]. Metabolic rate of 1.2 corresponds to CO₂ concentration of approximately 900 ppm, assuming outdoor CO₂ concentration of 400

ppm [89]. The study by Havenith (2007) has estimated metabolic rate (W.m^{−2}) of 9–11 years old primary school children for different school activities (language = 52, writing = 53, art = 59, drawing = 62 and calculus = 64 W m^{−2}) [32]. Metabolic rate of children [32] and adults [87] for different activities is shown in Table 4.

Calculated CO₂ generation rate per child according to equation (1) ranges from 3.34 to 5.89 cm³/s with a median of 3.41 cm³/s and mean of 3.64 cm³/s. Several other studies have reported similar CO₂ generations per child; 4.4–5.15 cm³/s in Ref. [28,29], 3.8–4 cm³/s in Refs. [26], 3.75–4.57 in Ref. [90], and 4.4 cm³/s in Ref. [27].

2.4. IAQ standards

The European standard of EN 13779:2007 [91] recommends IAQ values in four different building categories in Table 5. I) high level of expectation for spaces occupied by sensitive people, II) normal level of expectation for new buildings and renovations, III) moderate level of expectation for existing buildings and IV) low level of expectation only acceptable for a short period. The American Society of Heating, Refrigerating and Air-conditioning Engineers (ASHRAE) standard 62 recommends CO₂ level of 1000 ppm [92].

2.5. Statistical analysis

To decide on the most appropriate statistical test, the dependent variable and its type should be identified. To check the normality of CO₂ levels in this study, the histogram is used, as supported in Ref. [93]. Fig. 3 shows that CO₂ measurements are not normally distributed, therefore, none-parametric tests are used, as supported in Refs. [94,95].

Statistical analysis in this study are categorized into four main groups: 1) Descriptive, 2) Correlational, 3) predictive and 4) Group differences (cause and effect). Table 6 shows a summary of tests done in

Table 4

Metabolic rate of children and adults for different activities.

Children [32]			Adult [87]		
Type of activities for children	W/ m ²	MET	Type of activities for adults	W/ m ²	MET
Seated activities (working individually, listening, writing and following)	58	1	Seated activities (Office, dwelling, school, laboratory)	70	1.2
Standing (walking through classroom to get material and light manual work)	79	1.3	Standing (shopping, laboratory, light industry)	93	1.6
Standing, medium activity (signing and adjusting clothing for PE)	99	1.7	Standing, medium activity (shop assistant, domestic and machine work)	116	2

Table 5
Recommended CO₂ values by EN 13779:2007 [91].

Categories	IAQ standard	Typical Range	Total CO ₂ values Based on outdoor CO ₂ of 400 ppm
Category I	High	<400	<800
Category II	Medium	400–600	800–1000
Category III	Moderate	600–1000	1000–1400
Category IV	Low	>1000	>1400

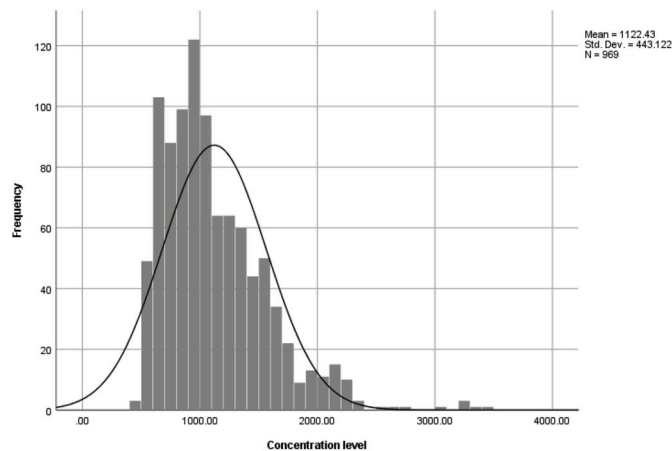


Fig. 3. Histogram and distribution of CO₂ measurements in classrooms.

this study based on the type of dependent and independent variables.

Descriptive statistics: For continuous normally distributed data, mean and standard deviations are used [96] and for skewed data with influential outliers, median and interquartile range are more appropriate [96,97]. Therefore, in this study, alongside descriptive statistics (minimum, maximum, mean and standard deviation) [96], median and interquartile range are also used for describing CO₂ levels.

Correlational: Correlation indicates both the strength and direction of the relationship between a pair of variables [94,95]. Cohen has proposed classifications for the strength of correlations using *r* values; 0.10 to 0.30 is taken as a weak correlation, 0.30 to 0.50 as a moderate correlation and more than 0.50 as a strong correlation [98]. It is assumed that higher absolute values and smaller associated *P* values imply a stronger correlation [99]. Spearman's correlation is a non-parametric statistical measure for the strength of the relationship between paired

Table 6
Summary of all tests in this study.

Variables		Corresponding Test	Variables in this Study	
Independent (IV)	Dependent (DV)		Dependent	Independent
1 interval IV	ordinal or interval (Skewed Data)	Spearman correlation test [93–95]	CO ₂ levels	Open area (m ²) G (cm ³ /s) OD (m ² /p, m ³ /p)
1 IV with 2 levels	ordinal or interval (Skewed Data)	Mann-Whitney test [93–97]	CO ₂ levels	Two Seasons Occupied groups (teaching and break)
1 IV with 2 or more groups	ordinal or interval (Skewed Data)	Non-parametric Kruskal-Wallis test [93–96]	CO ₂ levels	Categories for ABs (potential and practice) Categories of occupant-related factors

data, used for ordinal/interval and skewed data [93–96]. Unlike Pearson's *r*, Spearman's rho can be used in a wide variety of contexts since they make fewer assumptions about variables [94,95].

Predictive (Regression): Regression is concerned with making predictions [94,95] and it predicts dependent variable (*y*) given the independent variable (*x*) [96]. Regression explains how variables are related to produces a line of best fit ($y = a + bx + e$, $R^2 = n$), where *y* is dependent and *x* is the independent variable [96]. The R^2 value shows the proportion of the variation in the dependent variable which is explained by the model [94–96], or is the measure of how much of the variability in the outcome is accounted for the predictors [100].

In this study, correlations and regressions are used to show how CO₂ levels are related to open area (m²), *G* (cm³/s) and OD (m²/p, m³/p), Table 6.

Group differences: These tests compare the medians of groups, such as Mann-Whitney test [93–97] or Kruskal-Wallis [93–95] to determine whether the groups are the same or not. In this study, Mann-Whitney and Kruskal-Wallis tests are used to show how mean and median CO₂ levels change in different categories, Table 6.

The data were analysed using the Statistical Package for Social Science (SPSS) [101].

2.6. Overview of the recorded data

Descriptive statistics of CO₂ levels during teaching and total occupied period (teaching + non-teaching) are presented for non-heating and heating seasons in Table 7. The study on a total of 969 CO₂ measurements in 29 classrooms shows that mean and median concentrations are 1155 and 1063 ppm during teaching period, and 1122 ppm and 1021 ppm during total occupied period, Table 7.

Fig. 4 shows median CO₂ levels for teaching and total occupied period during both seasons. Median values for teaching and total occupied period are 1002 and 953 ppm during non-heating seasons and 1125 ppm and 1084 ppm during heating seasons.

Fig. 5 shows the number of classrooms with high and low potentials for ABs in each category of IAQ. Fig. 5 suggests that 23% of classrooms with high potentials for ABs and 56% classrooms with low potentials for ABs provide CO₂ levels lower than 1000 ppm. Fig. 6 shows the number of renovated and existing classrooms in each category of IAQ. Fig. 6 suggests that 46% renovated classrooms and 44% of existing classrooms provide CO₂ levels lower than 1000 ppm.

3. Results and analysis

3.1. CO₂ concentration

This section provides an overview of CO₂ measurements and their comparison with those in other studies.

Distribution of CO₂ level: Frequency (%) of CO₂ measurements falling in four categories of EN 13779:2007 [91] is shown in Fig. 7. During non-heating seasons, 29.1% of CO₂ measurements fall in category I (CO₂ < 800 ppm), 20.1% in category II (800 < CO₂ < 1000 ppm), 27.5% in category III (1000 < CO₂ < 1400 ppm) and 23.2% in category IV (CO₂ > 1400 ppm), Fig. 7. During heating seasons, 13% of CO₂ measurements fall in category I, 27% in category II, 30.6% in category III and 29.4% in category IV, Fig. 7. Category I has the highest frequency (29.1%) of CO₂ measurements during non-heating seasons and category III has the highest frequency (30.6%) during heating seasons.

Overall, 45% of CO₂ measurements in this study are below 1000 ppm and 55% of all CO₂ measurements are above 1000 ppm. In a similar study, 53% of CO₂ measurements exceed concentration value of 1000 ppm due to classrooms' insufficient ventilation. Results of another study show that 17% of the measurements exceeded CO₂ level of 1,150 ppm, only 22.5% exceeded ASHRAE's upper limit of 1,000 ppm, and 34% exceeded CO₂ level of 850 ppm [59], because windows and doors were usually kept open during most of occupancy hours [59].

Table 7
Descriptive Statistics of CO₂ levels for teaching and total period.

Mode	Period	N	Minimum	Maximum	Mean	Median	S.D.
Non-heating (NH)	Teaching	359	475	3360	1087	1002	440
	Total	526	475	3430	1050	953	444
Heating (H)	Teaching	358	555	2269	1224	1125	422
	Total	443	555	2659	1208	1084	427
Whole Year (WY)	Teaching	717	475	3360	1155	1063	436
	Total	969	475	3430	1122	1021	443

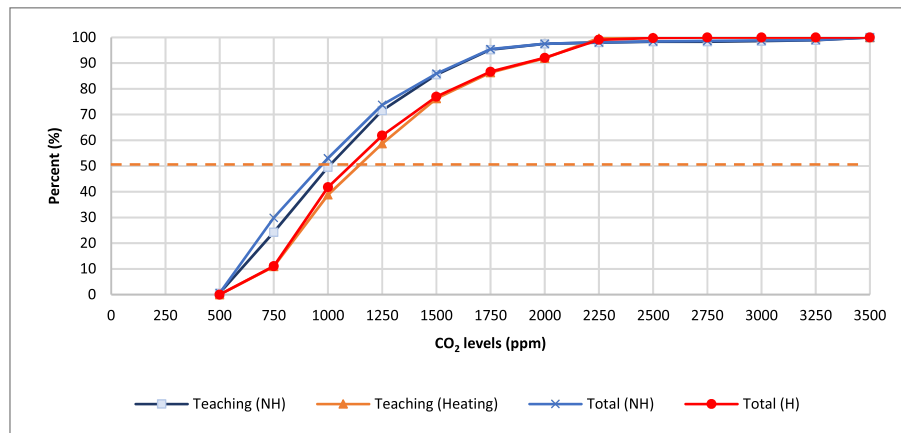


Fig. 4. Cumulative frequency (%) of CO₂ measurements.

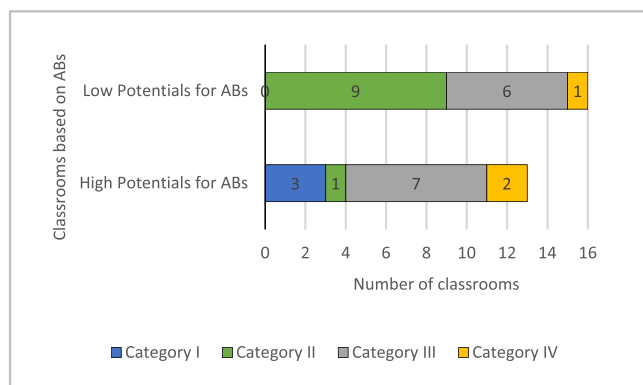


Fig. 5. Number of classrooms with high and low potentials for ABs in each category of IAQ.

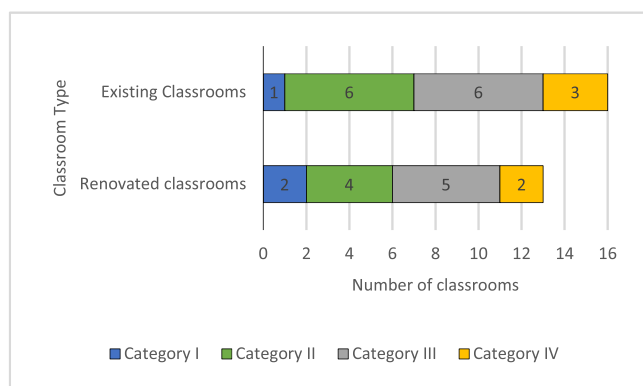


Fig. 6. Number of renovated and existing classrooms in each category of IAQ.

Mean and Median CO₂ levels: In this study, mean CO₂

concentrations during teaching periods [1087(NH), 1224(H) and 1155 (T)] are above 1000 ppm which is recommended by ASHRAE standard 62 [92] and several other studies [3]. Average CO₂ level in this study is higher than average of 1070 ppm in Ref. [25] due to frequent window openings [25] and it is lower than average of 1957 ppm in Refs. [26] due to not frequent window opening [26]. In this study, mean CO₂ concentration for total occupied period (T) is slightly lower than that for teaching period because total period includes non-teaching period with low occupancy density. This finding is supported in Ref. [30] with lower CO₂ levels during non-teaching period (1055 ppm) than teaching period (1482 ppm) [30]. In this study, daily mean concentrations exceed 1000 ppm in 55% of the classes, exceed 1500 ppm in 10% of the cases and exceed 2000 in 3% of cases. In a similar study [25], daily mean concentrations exceed 1000 ppm in 52% of NV classes, exceed 1500 ppm in 29% of cases and exceed 2000 ppm in 10% of classes [25]. In another study, median CO₂ level during school day exceeds 1000 ppm in only 28% of classrooms due to use of mechanical ventilation systems in Ref. [90].

3.2. CO₂ levels and occupant-related factors

Occupant-related factors that affect IAQ including occupants' adaptive behaviours, occupancy patterns, occupants' CO₂ generation rate and occupancy density are presented in Fig. 8.

3.2.1. Occupants' adaptive behaviours (ABs)

Due to the significant effect of adaptive behaviours on IAQ [26,59, 102,103], this study focuses on window operation as the main environmental practice.

Window Operations; Potentials and Practices: In this study, 45% of classrooms provide high potentials for practising ABs, however, it is also important to consider school occupant's practice of environmental ABs. This study introduces two terms of 'good practice' and 'poor practice' for occupants' environmental ABs. Good practice suggests occupants' adequate operation of windows to erase accumulated CO₂ concentrations (average open area more than 50% in each classroom)

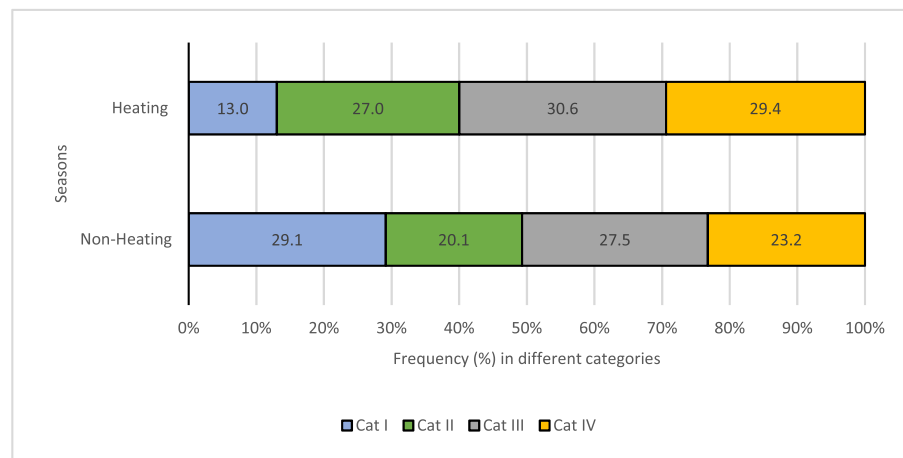


Fig. 7. Frequency (%) of CO₂ measurements falling in four categories of IAQ.

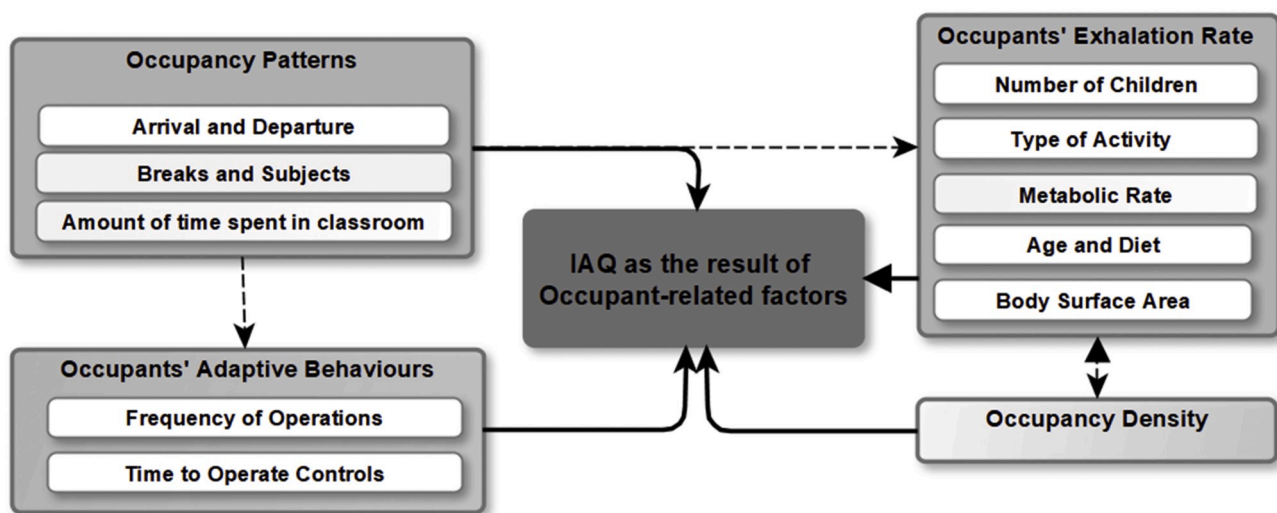


Fig. 8. A summary of occupant-related factors affecting IAQ.

and poor practice suggests occupants' inadequate window operation to provide IAQ (average open area less than 50% in each classroom).

The study has defined four groups of ABs based on potentials and practices; 1) High potentials and good practice, 2) High potentials and poor practice, 3) Low potentials and poor practice, 4) Low potentials and good practice. Results of the Kruskal-Wallis test show that there is a significant difference in median CO₂ levels [$X^2(3) = 24.3$, $p = 0.001$] between these defined groups, Fig. 9. To test categorical independent (such as groups of ABs) with interval dependent (such as CO₂ levels), analysis of covariance is used. Mean CO₂ levels in defined categories are 896, 1459, 1380 and 1007 ppm, respectively. Mean CO₂ level is lowest in group 1 (high potentials and good practice) and then in group 4 (low potentials and good practice), Fig. 9. Classrooms with good practice (mean = 896 and 1007) compared to classrooms with poor practice (mean = 1459 and 1380) can provide lower CO₂ levels disrespectful of their potentials for ABs. Results show that to maintain mean and median CO₂ levels lower than 1000 ppm, classrooms with both high potentials and good practice are required, however, occupants' practice is more important than classrooms' potentials. This suggests that classrooms with high potentials do not necessarily lower CO₂ levels and good practice of ABs is also required.

It is shown that 'high performance' buildings do not determine CO₂ levels [27]; IAQ is mostly affected by maintenance, operation practices, operating schedule and teacher behaviour [27]. Another study indicates

that classrooms should be designed capable of supplying enough fresh air, however, occupants should avail themselves of this capability [26]. This study suggests that good practice of ABs at the right time can prevent CO₂ build-up and increase IAQ, as supported in Refs. [15,26,27,59,102,103]. A review of published studies spanning 1983–2013 suggests that behavioural changes have the potential to reduce indoor air pollution by 20%–98% in laboratory settings and 31%–94% in field settings [104].

Window Operation and Environmental Variables: In studied classrooms, teachers are mainly in charge of window operations, as supported in previous studies [40,105,106], and only 16% of operations are carried out by children. To discover how window openings are affected by environmental variables, CO₂ levels and operative temperatures (T_{op}) at which windows are opened and average CO₂ levels in corresponding classrooms are plotted in Fig. 10. Results of this study show that CO₂ levels at which windows are opened and average CO₂ levels in corresponding classrooms are strongly correlated (Spearman Correlation coefficient = 0.60, $P < 0.001$). According to Cohen's classification [98], high correlation coefficient and small P values suggest a strong correlation.

Results show that 52% and 16% of window openings occur when CO₂ levels are higher than 1000 and 1500 ppm, respectively. Around half (52%) of window openings in this study occur when CO₂ levels > 1000 ppm which can be attributed to following reasons: 1. Window

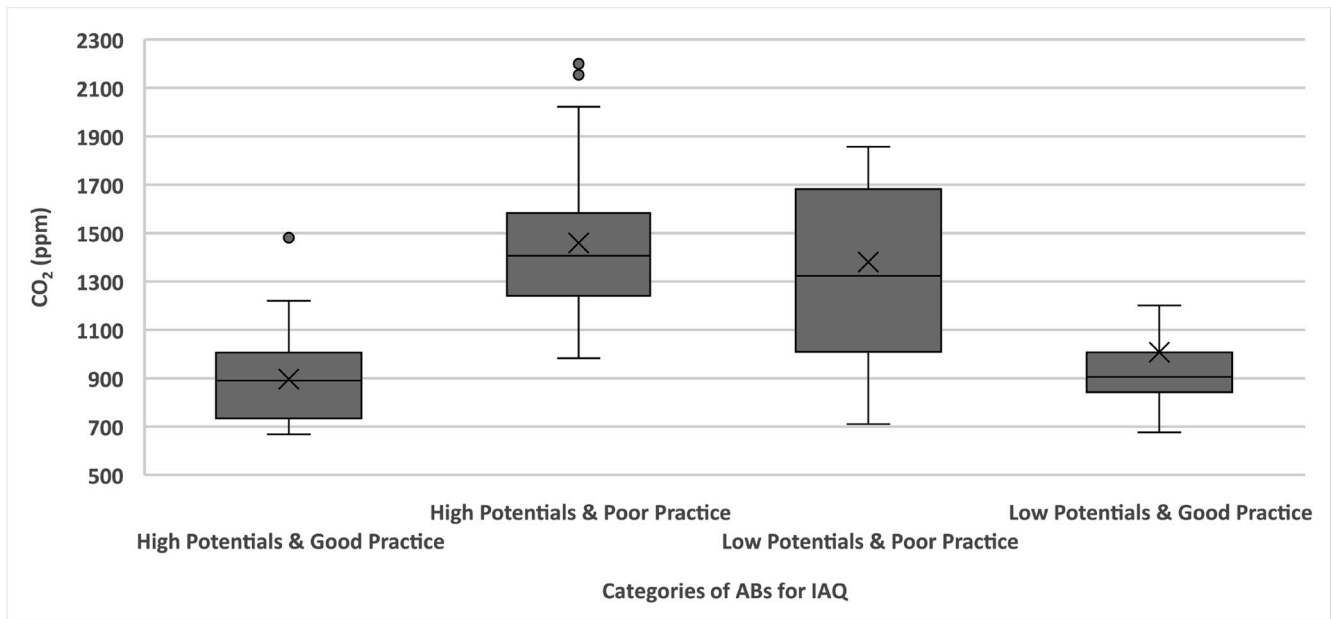


Fig. 9. CO₂ levels based on classrooms' potentials for natural ventilation and practice of ABs.

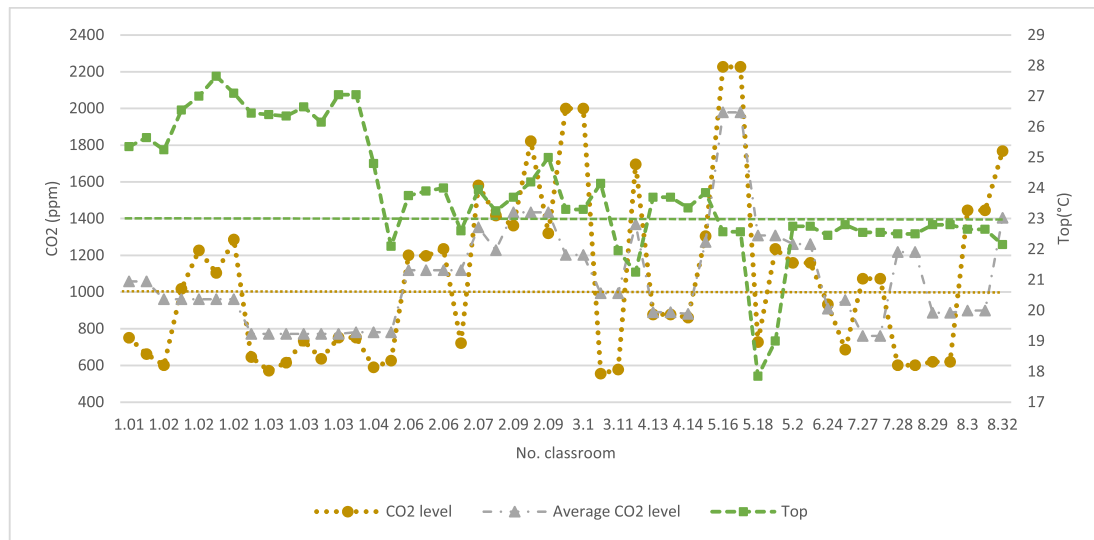


Fig. 10. CO₂ levels and T_{op} at which windows are opened and average CO₂ levels in classrooms.

operation can be affected by inappropriate design of windows and controls, as supported in Refs. [20,52]. Furthermore, some openings are not designed based on children's ergonomics [51,52]. In this study, 55% of classrooms provide low potentials for practice of ABs. 2. Window operation is more limited and less frequent among children than their teachers as they are mainly in charge of controlling classroom condition [40,52,56,105]. Authors highlight that only 16% of environmental ABs are done by children in this study due to the above reasons. 3. Window operation can also be affected by operative temperature. Teachers who are mainly in charge of the classrooms have higher comfort temperature than children [52,105,107]. According to an earlier study by authors [52], the upper limit of thermal comfort band for studied children is around 23 °C in this study, while for their teacher the upper limit is higher. Fig. 10 shows that among cases that window opening occurs at CO₂ levels higher than 1000 ppm, 20% of them have $T_{op} < 23$ °C. This suggests that despite high concentrations (CO₂ > 1000 ppm), windows were kept closed by teachers to avoid their thermal discomfort in 20% of

the cases.

Windows' Open Area and IAQ: Occupants' environmental adaptive behaviours by changing total open areas (open windows and external doors) affect IAQ. Results show that CO₂ levels and total open areas are significantly correlated during non-heating (Spearman Correlation coefficient = -0.32 , $P < 0.001$) and heating seasons (Spearman Correlation coefficient = -0.45 , $P < 0.001$). Results suggest negative moderate correlations between CO₂ levels and total open areas for non-heating (-0.32) and heating seasons (-0.45). To investigate how changes in CO₂ levels are explained by total open areas (m²), open areas and CO₂ measurements at 10-min intervals are plotted in Fig. 11. R² values in Fig. 11 suggest that 13% and 31% of CO₂ variations are explained by open areas during non-heating and heating seasons, respectively. Combining data from heating and non-heating seasons suggest that 17% of CO₂ variations are explained by open areas.

Correlations and R² values between CO₂ levels and open areas are higher during heating seasons than non-heating seasons. It is mainly

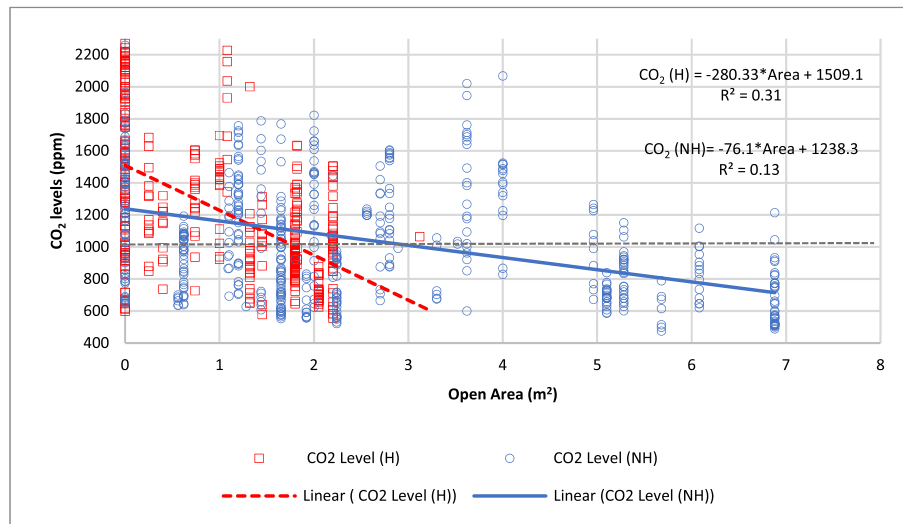


Fig. 11. The relationship between 'window area' and 'CO₂ levels' in classrooms.

because open areas during non-heating seasons are more correlated to T_{op} (Correlation coefficient = 0.53, $P < 0.001$) than CO₂ levels (Correlation coefficient = -0.32 , $P < 0.001$). However, open area during heating seasons is more related to CO₂ levels (Correlation coefficient = -0.45 , $P < 0.001$) than T_{op} (Correlation coefficient = 0.29, $P < 0.001$). Previous studies suggest that windows and doors are operated more when temperature is high [108,109] rather than when IAQ is poor [110], mainly because poor IAQ is not perceived due to gradual sensory fatigue or adaptation [15,111].

Window operation and Seasonal Changes: There is evidence that seasonal variations affect CO₂ concentrations indirectly by changing occupants' ABs [112]. Figs. 12 and 13 show changes in CO₂ levels and open areas during non-heating and heating seasons. Results of Mann-Whitney test in this study confirm that median CO₂ levels are significantly different during heating and non-heating seasons ($U = 88399$, $p = 0.000$). These Figures show that mean and median CO₂ levels are 137 ppm and 123 ppm higher during heating seasons than non-heating seasons due to lower average open areas during heating seasons (0.8 m^2) than non-heating seasons (2.4 m^2). Window operation is less frequent during heating seasons due to cold or draught [22,24,74,113] and energy consumption [110], which results in lower average open areas. It is shown that meeting IAQ requirements without comprising thermal comfort is difficult during heating season [113].

Results of a similar study show that median CO₂ values during

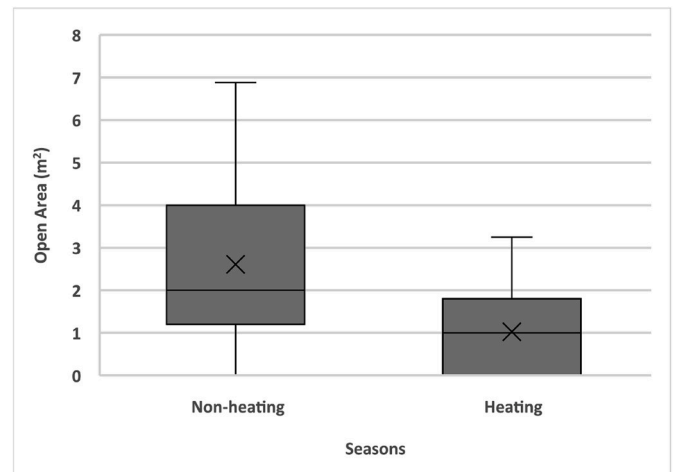


Fig. 13. Open areas (m²) during non-heating and heating seasons.

heating seasons ($1400 < \text{Median}_{\text{CO}_2} < 3000 \text{ ppm}$) are higher than those during non-heating seasons ($\text{Median}_{\text{CO}_2} < 1000 \text{ ppm}$), which is due to higher open windows during non-heating seasons [5]. Average CO₂ concentrations are 1.2–3.5 times higher during heating seasons compared to non-heating seasons due to open windows during non-heating seasons [5]. Another study shows that average CO₂ concentration reaches to almost 2500 ppm in one of the schools due to limitations in window opening during the winter [38]. In another study, mean CO₂ concentrations remain below 1000 ppm in all schools during the summer [38].

Due to the effect of occupant behaviour on IAQ [103,104], motivating and training school occupants for appropriate adaptive behaviours help to improve IAQ [21]. Several studies have shown that CO₂ warning devices by reminding occupants of the time at which windows should be operated can decrease CO₂ levels [55,63,103,114,115].

3.2.2. Occupancy patterns:

There is evidence that occupancy patterns affect CO₂ levels generated in indoor environment [23,25,28,41,74,85,102,116,117]. An overview of the results in this study shows that occupancy patterns and CO₂ levels in studied schools are dynamic and varied, as suggested in similar studies [112]. Fig. 14 shows mean and median CO₂ values from all 29 classrooms against time of day. As can be seen in Fig. 14, mean and

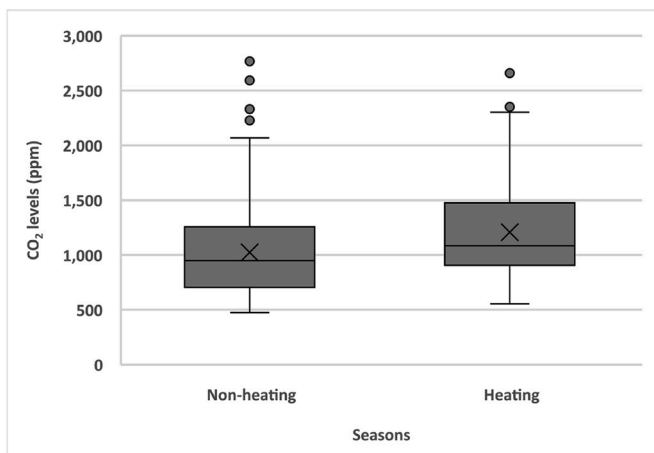


Fig. 12. CO₂ levels during non-heating and heating seasons.

median lines are similar which suggests data's symmetrical distribution. Similar studies support that small difference between mean and median shows symmetrical distribution [96].

The observation and trend suggest that teachers usually arrive before children at 8:00 and they possibly operate windows based on the classroom's temperature and IAQ. Children get into the classroom around 8:40–08:50 to start teaching session at around 9:00. Children often remain in the classroom for 2 h before they leave for a short break (10:50–11:10 a.m.). According to Fig. 14, mean CO₂ concentration goes up to 1350 ppm until the first break and reduces to 1190 ppm during the first break (12% reduction). Breaks are not long enough to decrease CO₂ levels significantly, however, longer breaks for assembly or Physical Education (PE) can decrease CO₂ levels more noticeably. After the first break, children remain in the classroom until lunch break (12:10–13:10). Longer lunch breaks can lower mean CO₂ levels from 1250 ppm to around 800 ppm (36% reduction). After lunch break, mean and median CO₂ levels usually increase until the end of afternoon session (15:20). It is shown that periodical absence of students during recess times is one of the main reasons behind periodical drop and rise of CO₂ concentrations in classrooms [41]. This trend for rising and fall of CO₂ levels in studied schools is suggested in several other studies [90, 102].

Fig. 14 shows that mean and median CO₂ levels are higher at the end of morning sessions (approximately 12:20 pm) compared to afternoon sessions (approximately 3:30 pm) due to longer morning sessions and accordingly more CO₂ built-up. Furthermore, longer lunch breaks (causing 36% reduction in CO₂ levels) compared to short breaks (causing 12% reduction in CO₂ levels) can clear accumulated CO₂ levels more significantly, as supported in Ref. [59]. Results of another study show the effect of scheduled breaks on maintaining CO₂ levels in different building types; 35% reduction for renovated schools, 25% reduction for new schools and 5% reduction for old schools [74]. The reduction of 160 ppm during the first break which is usually around 20 min shows a decrease of 8 ppm/min among studied classrooms. Similarly, reduction of 450 ppm during lunch break which is usually around 50 min shows a decrease of 9 ppm/min. Speed of clearance 'ppm/min' is slightly higher during lunchtime than that during break which can be explained by larger open areas (2.3 m² v.s. 1.6 m²) during lunchtime. Another study by taking into account all school breaks from different buildings expects a reduction of 19.4 ppm/min [74], which gives a reduction of 250 ppm for a 13-min break [74]. Results of this study, as already supported in Ref. [74], suggest that although the effect of school breaks on decreasing pollutant concentration is significant, it is still insufficient to lower accumulated CO₂ levels within standards,

Fig. 14. That is where the effect of adaptive behaviours consistent with occupancy patterns becomes more important.

Figs. 15 and 16 show changes in CO₂ levels and open area in box plots. Results of Mann-Whitney test in this study confirm that median CO₂ levels are significantly different during teaching and break period ($U = 71293$, $p = 0.000$). These figures show that higher CO₂ levels during teaching period (1156 ppm) compared to breaks (1032 ppm) which can be explained by higher mean open area during breaks (2.1 m²) compared to teaching period (1.8 m²). It is suggested that windows are closed during teaching period due to low exterior temperatures [74] or outdoor noise [103]. Therefore, this study recommends that by leaving windows open during breaks, accumulated CO₂ levels can be cleared without comprising children's overall comfort, as supported in Refs. [41,74,103]. It is shown that IAQ during breaks can be 1–4 times higher than that during teaching period [25].

3.2.3. Occupants' CO₂ generation (G) rates

Total CO₂ generation rate (G) from building occupants considers number of children, their age, metabolic rate, activity level, body surface area and room temperature [26]. In this study, children's generation rates are calculated at 10-min intervals due to varied occupancy patterns. Generation rates per child (3.34–5.89 cm³/s) are multiplied by the number of children for calculating children's generation rates at 10-min intervals. Generation rate of teachers (11 cm³/s) is added to this amount for total G. Fig. 17 shows box plots of total G for sedentary and non-sedentary activities. Mean G for sedentary activities (Reading and writing) equals to 97 cm³/s and for non-sedentary activities (Standing

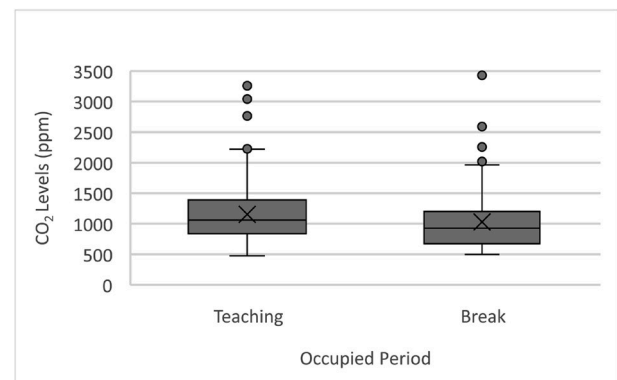


Fig. 15. Changes in CO₂ levels during occupied period.

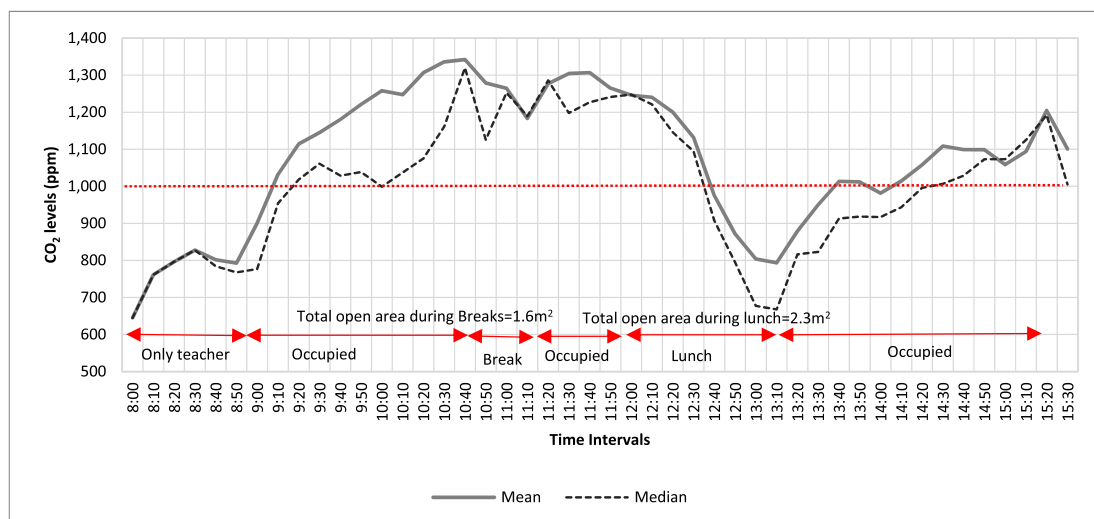


Fig. 14. The trend for rising and fall of CO₂ levels during school occupancy based on 29 classrooms.

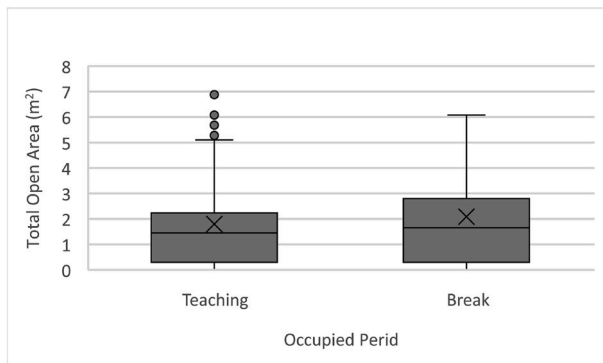


Fig. 16. Changes in open area during occupied period.

and walking) equals to $132 \text{ cm}^3/\text{s}$, Fig. 17. Similar studies support that students' activity intensity contribute to classrooms' CO_2 concentrations [85,116]. Effect of 'activity type' on CO_2 levels is more noticeable when two classrooms join for some activities or when children get back from play and bring a different heat load to classrooms [28].

Mean generation rates for sedentary activities in each classroom are plotted against mean CO_2 levels in Fig. 18. Results show that mean CO_2 levels and total generation rates are correlated (Spearman Correlation coefficient = 0.17, $P < 0.001$). R^2 value suggests that 14% of CO_2 variations are explained by average G, Fig. 18.

Considering average number of students in this study (25) and one standing teacher, total generation rate for sedentary activities is estimated at around $102 \text{ cm}^3/\text{s}$. According to Fig. 18, corresponding average CO_2 level for G value of $102 \text{ cm}^3/\text{s}$ is 1360 ppm. Considering that IAQ decreases when CO_2 production rate is greater than its removal rate [118], it is important to remove high emission rates from the building by the good practice of ABs.

3.2.4. Occupancy density (OD)

Accumulation of CO_2 levels vary within area and volume of the classroom, therefore, occupancy density should be considered for evaluating IAQ. Occupancy density is defined as the area per number of occupants (m^2/p) [119] or volume per number of occupants (m^3/p). In this study, occupancy density in m^2/p ranges from 1.7 to $2.6 \text{ m}^2/\text{p}$, with a mean of $2.1 \text{ m}^2/\text{p}$. Another study suggests occupancy density of $1.8\text{--}2.4 \text{ m}^2/\text{p}$ for school classrooms which is significantly higher than that in offices ($10 \text{ m}^2/\text{person}$) [57]. Several studies suggest that occupancy density in schools is approximately four times higher than that in office buildings since school occupants are sitting very close [57,58,112]. Occupancy densities (m^2/p) in classrooms are plotted against corresponding mean CO_2 levels in Fig. 19. Results show that CO_2 levels and OD (m^2/p) are correlated (Spearman Correlation coefficient = -0.14 , $P < 0.001$). R^2 value in Fig. 19 shows that 17% of CO_2 variations

are explained by occupancy density (m^2/p).

Occupancy densities (m^3/p) range from 4.3 to $9.1 \text{ m}^3/\text{p}$, with a mean of $6.3 \text{ m}^3/\text{p}$. Occupancy densities (m^3/p) in each classroom are plotted against mean CO_2 levels in Fig. 20. Results show that CO_2 levels and occupancy density (m^3/p) are correlated (Spearman Correlation coefficient = -0.13 , $P < 0.001$). R^2 value in Fig. 20 shows that 11% of the variations in average CO_2 levels are explained by occupancy density (m^3/p).

Figs. 19 and 20 display that high occupancy densities cause high CO_2 concentrations, as suggested in several other studies [5,55,57,85,102,103,118,120]. Results of this study show that to maintain the average CO_2 level of 1000 ppm, occupant density should be at least $2.3 \text{ m}^2/\text{p}$ and $7.6 \text{ m}^3/\text{p}$, Figs. 19 and 20. The suggested OD in this study complies with occupancy density recommended by Eurostat (2011), which is from 2 to $3.1 \text{ m}^2/\text{person}$ based on $20.8 + 2.0$ students for the average size of primary classrooms in European and American countries [121].

In this study, there are averagely 27 occupants (25 students + teacher + teacher assistant) in each classroom. Results of this study in Figs. 19 and 20 show that average occupancy densities to have CO_2 levels of $1000 \pm 50 \text{ ppm}$ is $2.3 \pm 0.05 \text{ m}^2/\text{p}$ and $7.6 \pm 0.25 \text{ m}^3/\text{p}$. These values correspond to classroom area and volume of $62.1 \pm 1.35 \text{ m}^2$ and $205.2 \pm 6.75 \text{ m}^3$ with a height of 3.3 m. Building Bulletin 99 (Briefing Framework for Primary School Projects) also suggests that the 'standard' size of a primary classroom for 30 pupils is around 70 m^2 (2.3 m^2 per person) [122]. Considering the shortage of space in the educational sector [123–125], if providing the recommended area is not possible for the designer, classrooms' height can be increased to more than 3.3 m to maintain the required volume for maintaining IAQ. The focus of guidelines for recommended OD (m^2/p) is mainly on providing the required area for children's physical activities. However, this study highlights the importance of all three dimensions in OD values (m^3/p) for maintaining IAQ. It is important to keep the number of children in proportion to the classroom's area and volume, also supported in Ref. [90], because overcrowded classrooms cause high CO_2 concentrations and high emissions of body odour [30,57,85,103,112,118]. It is shown that high-density classrooms, with too many children or too little space, lead to pupils' stress, reductions in desired privacy levels and loss of control [120].

4. Discussion

The study has investigated occupant-related factors that affect IAQ including occupants' adaptive behaviours, occupancy patterns, occupants' CO_2 generation rate and occupancy density. Table 8 shows correlations and R^2 Values between IAQ and occupant-related factors. Correlations and R^2 values in Table 8 suggest that among all occupant-related factors, occupant's adaptive behaviours have the strongest correlation (-0.40) with CO_2 levels and account for the highest CO_2 variation (17%).

Therefore, when children's number and type of activity result in high concentrations, good practice of ABs can clear accumulated CO_2 levels in classrooms.

4.1. Comparing classrooms' IAQ with standards

To evaluate IAQ in each classroom, average CO_2 levels in each classroom are compared with values recommended by EN 13779:2007 [91] and ASHRAE [92]. The last column in Table 9 shows occupant-related factors that potentially lead to high CO_2 levels in classrooms with the following acronyms:

- **AB for Adaptive Behaviours** when the poor practice of ABs is a potential reason for high CO_2 levels.
- **G for Generation Rate** when G higher than $102 \text{ cm}^3/\text{s}$ based on 25 sedentary students is a potential reason for high CO_2 levels.

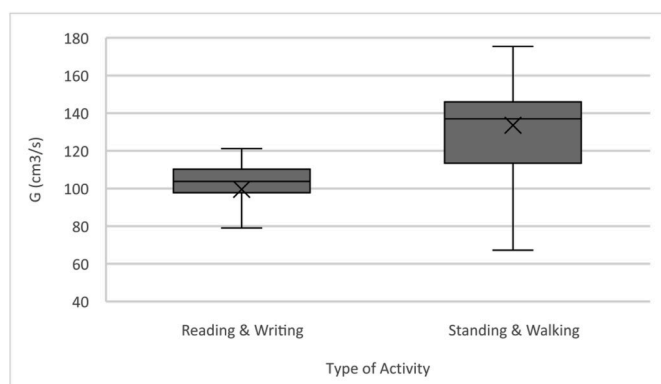


Fig. 17. Total G for different activities.

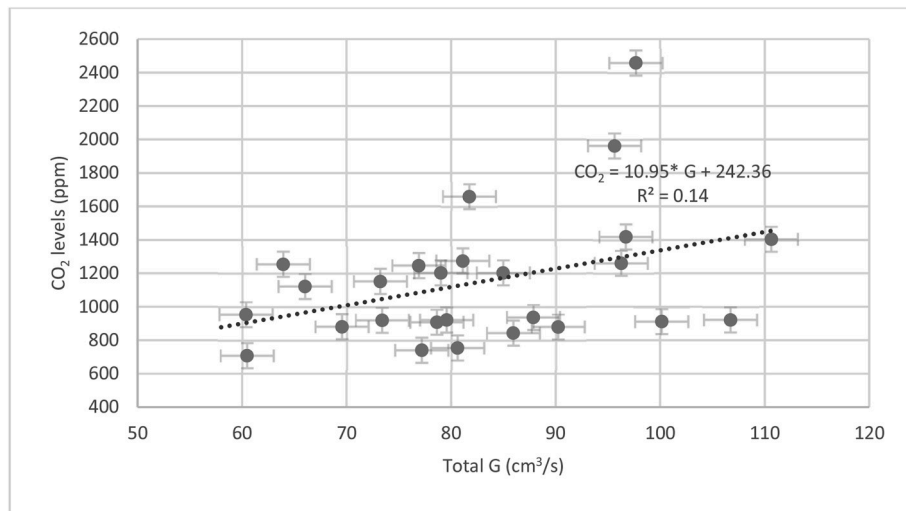


Fig. 18. Mean G in each classroom plotted against mean CO₂ levels for both sedentary activities.

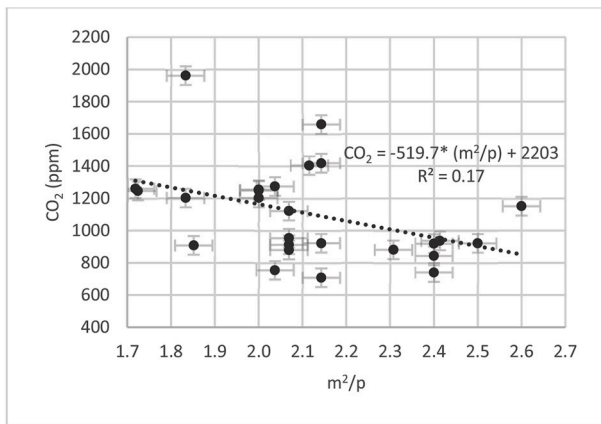


Fig. 19. Occupancy Density in m²/p plotted against mean CO₂ levels.

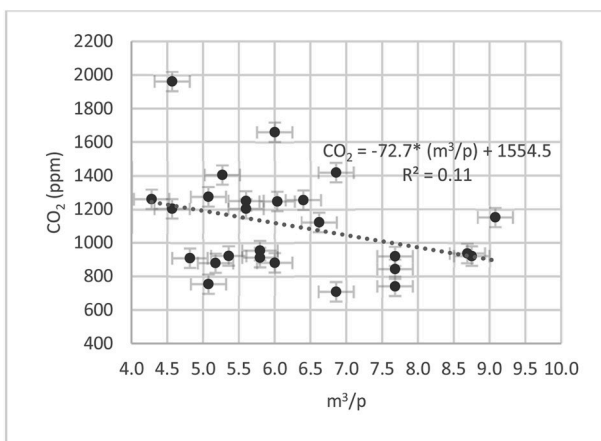


Fig. 20. Occupancy Density in m³/p plotted against mean CO₂ levels.

- **OD for Occupancy Density** when OD lower than 2.3 m²/p is a potential reason for high CO₂ levels.

As can be seen in Table 9, the reasons for high concentrations are related to one factor or a mix of occupant-related factors.

Fig. 21 shows changes in CO₂ levels by the change in occupant-

related factors. Results of the Kruskal-Wallis test show that there is a difference in median CO₂ levels [$X^2(2) = 6.6$, $p = 0.038$] when the number of favourable occupant-related factors are different, Fig. 21. According to Fig. 21, when all occupant-related factors can potentially reduce CO₂ levels, mean concentration is 893 ppm with the maximum of 964 ppm, when one or two occupant-related factors can potentially reduce CO₂ levels, mean concentration is 1122 ppm with the maximum of 1404 ppm and when none of the occupant-related factors can potentially reduce CO₂ levels, mean concentration is 1317 ppm with the maximum of 1979 ppm. This suggests that when all occupant-related factors are favourable, CO₂ levels below 1000 ppm can be maintained. However, when occupant-related factors are not favourable, it is less likely to maintain adequate CO₂ levels.

There is evidence that renovated schools provide more suitable conditions compared to non-renovated schools [21,38]. In this study, 54% of renovated classrooms have CO₂ (mean) > 1000 ppm, among which 73% with the poor practice of ABs. Furthermore, 73% of classrooms with high potentials for ABs have CO₂ (mean) > 1000 ppm, among which 69% with the poor practice of ABs. This suggests that to maintain IAQ in existing and renovated school buildings, more focus should be directed at school occupants, their occupancy patterns and adaptive behaviours.

5. Conclusion

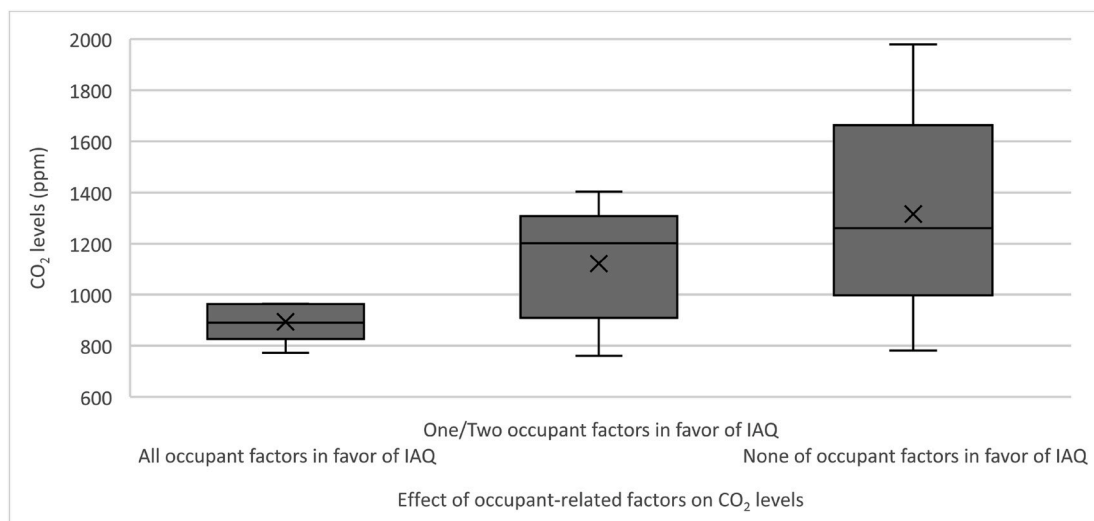
This paper was focused on occupants' role for maintaining IAQ in naturally-ventilated primary schools during heating and non-heating seasons. The study highlights that IAQ is closely related to occupants' adaptive behaviour, occupancy patterns, CO₂ generation rates and occupant density, however, the impact of occupants' adaptive behaviours is more significant. Although classrooms' potentials for facilitating adaptive behaviours is fundamental in maintaining IAQ, this study suggests that occupants' interaction with the building (i.e. Good Practice of ABs) is more significant. Therefore, there is a need to encourage and train school occupants (i.e. teachers and children) for Good Practice of Adaptive Behaviours. Furthermore, teachers will have more effective ABs if they are trained about the impact of occupancy patterns and generation rates on CO₂ built-up. For example, when windows are left open during breaks or lunchtime, accumulated CO₂ levels are cleared without comprising children's thermal comfort. Therefore, good practice of ABs is not only limited to occupants' interaction with controls but also related to the correct time for interaction to maintain other elements of comfort (i.e. thermal comfort). Available guidelines mainly focus on OD (m²/p) in two dimensions to provide the required area for children's physical activities in classrooms; however, this study

Table 8Correlation and R² values between CO₂ levels and occupant-related factors.

Occupant-related factors affecting IAQ	Correlation	P-value	Correlation by Cohen's Classification	R ² Value	Interpretation
Occupants' adaptive behaviours: Open Area	-0.40	P < 0.001	Negative Moderate	0.17	17% of CO ₂ variations are explained by open area (m ²)
Occupants' generation rates (cm ³ /s)	0.17	P < 0.001	Positive weak	0.14	14% of CO ₂ variations are explained by occupants' generation rates (cm ³ /s)
Occupancy density (m ² /p)	0.14	P < 0.001	Positive weak	0.17	17% of CO ₂ variations are explained by occupancy density (m ² /p).
Occupancy density (m ³ /p)	0.13	P < 0.001	Positive weak	0.11	11% of CO ₂ variations are explained by occupancy density (m ³ /p).

Table 9Comparing mean CO₂ levels in classrooms with Standards.

Type	No.	Potentials for ABs	Occupant-related factors					CO ₂	EN 13779 [91]	ASHRAE [92]	Factor
			Open Area	Practice of ABs	Total G	m ² /p	M ³ /p		CO ₂ level	CO ₂ level	
Renovated	1.1	H	5.8	H	164	2.1	6.6	1058	×	×	G, OD
	1.2	H	4.9	H	101	2.4	7.7	961	✓	✓	–
	1.3	H	5.3	H	101	2.4	7.7	772	✓	✓	–
	1.4	H	2.2	L	107	2.1	6.9	781	✓	✓	AB, G, OD
	2.6	H	1.1	L	115	2.2	7.0	1119	×	×	AB, G, OD
	2.7	H	1.2	L	77	3.5	11.2	1352	×	×	AB
	2.8	H	1.2	L	79	4.4	14.0	1228	×	×	AB
	2.9	H	2.5	L	114	2.1	6.9	1434	×	×	AB, G, OD
	3.10	L	0.9	L	89	3.1	10.9	1202	✓	×	AB
Existing	3.11	L	2.0	H	112	2.6	9.0	993	✓	✓	G
	3.12	L	0.6	L	62	4.2	13.5	1369	✓	×	AB
	4.13	L	1.6	H	90	2.5	6.4	890	✓	✓	–
	4.14	L	1.8	H	77	3.7	9.6	881	✓	✓	–
	4.15	L	0.0	L	103	2.2	7.7	1273	✓	×	AB, G, OD
	5.16	H	0.1	L	119	2.1	5.1	1979	×	×	AB, G, OD
	5.18	H	1.3	L	95	2.6	6.4	1308	✓	×	AB,
	5.20	H	1.0	L	105	2.5	6.2	1261	✓	×	AB, G
	6.21	L	1.3	H	84	2.3	6.4	964	✓	✓	–
Renovated	6.22	L	0.0	L	109	2.2	6.2	1740	×	×	AB, G, OD
	6.23	L	0.0	L	110	2.2	6.2	1249	×	×	AB, G, OD
	6.24	L	1.1	H	125	2.2	6.1	909	✓	✓	G, OD
	6.25	L	0.0	L	113	2.0	5.6	980	✓	✓	AB, G
	7.26	L	0.3	L	113	2.5	9.0	956	✓	✓	AB, G, OD
Existing	7.27	H	3.9	H	106	2.0	5.1	761	✓	✓	G
	7.28	H	3.0	L	108	1.9	4.6	1218	✓	×	AB, G
	8.29	L	1.7	H	107	2.3	5.6	887	✓	✓	G, OD
	8.30	L	1.6	H	111	2.1	5.4	899	✓	✓	G
	8.31	L	0.0	L	100	2.3	5.7	2487	×	×	AB, OD
	8.32	L	1.7	H	111	2.1	5.3	1404	×	×	G

**Fig. 21.** CO₂ level according to the numbers of favourable occupant-related factors.

underlines the importance of height as the third dimension in OD values (m^3/p) to maintain IAQ. This study suggests minimum occupancy densities of $2.3 \text{ m}^3/\text{p}$ and $7.6 \text{ m}^3/\text{p}$ for maintaining CO_2 level $<1000 \text{ ppm}$ in primary school classrooms.

Declaration of competing interest

none.

Acknowledgements

The authors would like to thank Professor James Brusey for his comments and insight that improved the paper. We would like to acknowledge headteachers, teachers and children in studied primary schools in Coventry for their cooperation. We appreciate financial support of Coventry University to complete this research.

References

- [1] D. Grimsrud, B. Bridges, R. Schulte, Continuous measurements of air quality parameters in schools, *Build. Res. Inf.* 34 (2006) 447–458, <https://doi.org/10.1080/09613210600808880>.
- [2] M.J. Mendell, G.A. Heath, Do indoor pollutants and thermal conditions in schools influence student performance? A critical review of the literature, *Indoor Air* 15 (2005) 27–52, <https://doi.org/10.1111/j.1600-0668.2004.00320.x>.
- [3] L. Chatzidiakou, D. Mumovic, A. Summerfield, Is CO_2 a good proxy for indoor air quality in classrooms? Part 2: health outcomes and perceived indoor air quality in relation to classroom exposure and building characteristics, *Build. Serv. Eng. Technol.* 36 (2015) 162–181, <https://doi.org/10.1177/0143624414566245>.
- [4] J.M. Daisey, W.J. Angell, M.G. Apte, Indoor air quality, ventilation and health symptoms in schools: an analysis of existing information, *Indoor Air* 13 (2003) 53–64, <https://doi.org/10.1034/j.1600-0668.2003.00153.x>.
- [5] L. Stabile, M. Dell, A. Russi, A. Massimo, G. Buonanno, The effect of natural ventilation strategy on indoor air quality in schools, *Sci. Total Environ.* 595 (2017) 894–902, <https://doi.org/10.1016/j.scitotenv.2017.03.048>.
- [6] U. Satish, M.J. Mendell, K. Shekhar, T. Hotchi, D. Sullivan, S. Streufert, W.J. Fisk, Is CO_2 an indoor pollutant? Direct effects of low-to-moderate CO_2 concentrations on human decision-making performance, *Environ. Health Perspect.* 120 (2012) 1671–1677.
- [7] P.V. Dorizas, M. Assimakopoulos, M. Santamouris, A holistic approach for the assessment of the indoor environmental quality, student productivity, and energy consumption in primary schools, *Environ. Monit. Assess.* 187 (2015) 4503, <https://doi.org/10.1007/s10661-015-4503-9>.
- [8] W.H. Organization, WHO Guidelines for Indoor Air Quality, Sel. Pollut. Copenhagen, Denmark WHO, 2010.
- [9] O.A. Seppänen, W.J. Fisk, M.J. Mendell, Association of ventilation rates and CO_2 concentrations with health and other responses in commercial and institutional buildings, *Indoor Air* 9 (1999) 226–252.
- [10] D.A. Coley, R. Greeves, B.K. Saxby, The effect of low ventilation rates on the cognitive function of a primary school class, *Int. J. Vent.* 6 (2007) 107–112, <https://doi.org/10.1080/101016107011683770>.
- [11] D. Twardella, W. Matzen, T. Lahrz, R. Burghardt, H. Spiegel, L. Hendrowsarsito, A. C. Frenzel, H. Fromme, Effect of classroom air quality on students' concentration: results of a cluster-randomized cross-over experimental study, *Indoor Air* 22 (2012) 378–387.
- [12] Z. Bakó-Biró, D.J. Clements-Croome, N. Kochhar, H.B. Awbi, M.J. Williams, Ventilation rates in schools and pupils' performance, *Build. Environ.* 48 (2012) 215–223, <https://doi.org/10.1016/j.buildenv.2011.08.018>.
- [13] A.N. Myhrvold, E. Olsen, O. Lauridsen, Indoor environment in schools—pupils health and performance in regard to CO_2 concentrations, *Indoor Air* 96 (1996) 369–371.
- [14] Z. Bakó-biró, D.J. Clements-croome, N. Kochhar, H.B. Awbi, M.J. Williams, Ventilation rates in schools and pupils' performance, *Build. Environ.* 48 (2012) 215–223, <https://doi.org/10.1016/j.buildenv.2011.08.018>.
- [15] D. for E. and S. (DfES), Building Bulletin 101: Guidelines on Ventilation, Thermal Comfort and Indoor Air Quality in Schools, DfES London, 2016.
- [16] L. Chatzidiakou, D. Mumovic, A. Summerfield, Is CO_2 a good proxy for indoor air quality in classrooms? Part 1: the interrelationships between thermal conditions, CO_2 levels, ventilation rates and selected indoor pollutants, *Build. Serv. Eng. Technol.* 36 (2015) 129–161, <https://doi.org/10.1177/0143624414566244>.
- [17] A. Astolfi, F. Pellerey, Subjective and objective assessment of acoustical and overall environmental quality in secondary school classrooms, *J. Acoust. Soc. Am.* 123 (2008) 163–173, <https://doi.org/10.1121/1.2816563>.
- [18] M.G. Apte, W.J. Fisk, J.M. Daisey, Indoor carbon dioxide concentrations and SBS in office workers, in: *Proc. Heal. Build.*, 2000, p. 133.
- [19] D. Norbäck, K. Nordström, An experimental study on effects of increased ventilation flow on students' perception of indoor environment in computer classrooms, *Indoor Air* 18 (2008) 293–300, <https://doi.org/10.1111/j.1600-0668.2008.00530.x>.
- [20] S.S. Korsavi, A. Montazami, J. Brusey, Developing a design framework to facilitate adaptive behaviours, *Energy Build.* 179 (2018) 360–373, <https://doi.org/10.1016/j.enbuild.2018.09.011>.
- [21] A. Heeboll, P. Wargocki, Jø Toftum, Window and door opening behavior, carbon dioxide concentration, temperature, and energy use during the heating season in classrooms with different ventilation retrofits—ASHRAE RP1624, *Sci. Technol. Built Environ.* 4731 (2018) 1–12, <https://doi.org/10.1080/23744731.2018.1432938>.
- [22] N. Canha, S.M. Almeida, M.C. Freitas, M. Täubel, O. Hänninen, Winter ventilation rates at primary Schools : comparison between Portugal and Finland, *J. Toxicol. Environ. Health Part A* 76 (6) (2013) 400–408, <https://doi.org/10.1080/15287394.2013.765372>.
- [23] V. Turanjanin, B. Vučićević, M. Jovanović, N. Mirkov, I. Lazović, Indoor CO_2 measurements in Serbian schools and ventilation rate calculation, *Energy* 77 (2014) 290–296, <https://doi.org/10.1016/j.energy.2014.10.028>.
- [24] J. Gao, P. Wargocki, Y. Wang, Ventilation system type, classroom environmental quality and pupils' perceptions and symptoms, *Build. Environ.* 75 (2014) 46–57, <https://doi.org/10.1016/j.buildenv.2014.01.015>.
- [25] M. Santamouris, A. Synnefa, M. Assimakopoulos, I. Livada, K. Pavlou, M. Papaglastra, N. Gaitani, D. Kolokotsa, V. Assimakopoulos, Experimental investigation of the air flow and indoor carbon dioxide concentration in classrooms with intermittent natural ventilation, *Energy Build.* 40 (2008) 1833–1843, <https://doi.org/10.1016/j.enbuild.2008.04.002>.
- [26] D.A. Coley, A. Beisteiner, Carbon dioxide levels and ventilation rates in schools, *Int. J. Vent.* 1 (2002) 45–52, <https://doi.org/10.1080/14733315.2002.11683621>.
- [27] S. Batterman, F.C. Su, A. Wald, F. Watkins, C. Godwin, G. Thun, Ventilation rates in recently constructed US school classrooms, *Indoor Air* 27 (5) (2017) 880–890, <https://doi.org/10.1111/ina.12384>.
- [28] M.B. Luther, P. Horan, O. Tokede, Investigating CO_2 concentration and occupancy in school classrooms at different stages in their life cycle, *Archit. Sci. Rev.* 8628 (2017) 1–13, <https://doi.org/10.1080/00038628.2017.1416576>.
- [29] M.B. Luther, P. Horan, Investigating and understanding CO_2 levels in school classrooms, in: *ANZAScA Proc. 48th Int. Conf. Archit. Sci. Assoc. ANZAScA Archit. Sci. Assoc.*, 2014, pp. 631–641.
- [30] P.V. Dorizas, M.N. Assimakopoulos, C. Helmis, M. Santamouris, An integrated evaluation study of the ventilation rate, the exposure and the indoor air quality in naturally ventilated classrooms in the Mediterranean region during spring, *Sci. Total Environ.* 502 (2015) 557–570, <https://doi.org/10.1016/j.scitotenv.2014.09.060>.
- [31] S.P. Corgnati, R. Ansaldi, M. Filippi, Thermal comfort in Italian classrooms under free running conditions during mild seasons: assessment through objective and subjective approaches, *Build. Environ.* 44 (2009) 785–792, <https://doi.org/10.1016/j.buildenv.2008.05.023>.
- [32] G. Havenith, Metabolic rate and clothing insulation data of children and adolescents during various school activities, *Ergonomics* 50 (2007) 1689–1701, <https://doi.org/10.1080/00140130701587574>.
- [33] D. Teli, P.A.B.B. James, M.F. Jentsch, Thermal comfort in naturally ventilated primary school classrooms, *Build. Res. Inf.* 41 (2013) 301–316, <https://doi.org/10.1080/09613218.2013.773493>.
- [34] R.-L. Hwang, T.-P. Lin, C.-P. Chen, N.-J. Kuo, Investigating the adaptive model of thermal comfort for naturally ventilated school buildings in Taiwan, *Int. J. Biometeorol.* 53 (2009) 189–200, <https://doi.org/10.1007/s00484-008-0203-2>.
- [35] H. Yun, I. Nam, J. Kim, J. Yang, K. Lee, J. Sohn, A field study of thermal comfort for kindergarten children in Korea: an assessment of existing models and preferences of children, *Build. Environ.* 75 (2014) 182–189, <https://doi.org/10.1016/j.buildenv.2014.02.003>.
- [36] G. Buonanno, L. Morawska, L. Stabile, L. Wang, G. Giovino, A comparison of submicrometer particle dose between Australian and Italian people, *Environ. Pollut.* 169 (2012) 183–189.
- [37] M.K. Selgrade, C.G. Plopper, M.I. Gilmour, R.B. Conolly, B.S.P. Foos, Assessing the health effects and risks associated with children's inhalation exposures—asthma and allergy, *J. Toxicol. Environ. Health Part A* 71 (2007) 196–207.
- [38] R.M.S.F. Almeida, V. Peixoto, D. Freitas, V.P. De Freitas, Indoor environmental quality of classrooms in Southern European climate, *Energy Build.* 81 (2014) 127–140, <https://doi.org/10.1016/j.enbuild.2014.06.020>.
- [39] S.C. Lee, M. Chang, Indoor and outdoor air quality investigation at schools in Hong Kong, *Chemosphere* 41 (1–2) (2000) 109–113, [https://doi.org/10.1016/S0045-6535\(99\)00396-3](https://doi.org/10.1016/S0045-6535(99)00396-3).
- [40] V. De Giuli, O. Da Pos, M. De Carli, Indoor environmental quality and pupil perception in Italian primary schools, *Build. Environ.* 56 (2012) 335–345, <https://doi.org/10.1016/j.buildenv.2012.03.024>.
- [41] S. Vilcekova, L. Meciarova, E.K. Burdova, J. Katunská, D. Kosicanova, S. Doroudiani, Indoor environmental quality of classrooms and occupants' comfort in a special education school in Slovak Republic, *Build. Environ. Times* 120 (2017) 29–40, <https://doi.org/10.1016/j.buildenv.2017.05.001>.
- [42] Rcpch, Uk-World Health, Organisation Growth Charts - 2-18 Years, n.d. <http://www.rcpch.ac.uk/resources/uk-world-health-organisation-growth-charts-2-18-years>.
- [43] J. Cieniewicz, S. Trivedi, S.R. Kleeberger, Oxidants and the pathogenesis of lung diseases, *J. Allergy Clin. Immunol.* 122 (2008) 456–468.
- [44] K.R. Smith, J.M. Samet, I. Romieu, N. Bruce, Indoor air pollution in developing countries and acute lower respiratory infections in children, *Thorax* 55 (6) (2000) 518–532, <https://doi.org/10.1136/thorax.55.6.518>.

- [45] P. Wargocki, D.P. Wyon, The effects of outdoor air supply rate and supply air filter condition in classrooms on the performance of schoolwork by children (RP-1257), HVAC R Res. 12 (2007) 165–191.
- [46] K.K. Kalimeri, D.E. Saraga, V.D. Lazaridis, N.A. Legkas, D.A. Missia, E.I. Tolis, J. G. Bartzis, Indoor air quality investigation of the school environment and estimated health risks : two-season measurements in primary schools in Kozani , Greece, Atmos. Pollut. Res. 7 (2016) 1128–1142, <https://doi.org/10.1016/j.apr.2016.07.002>.
- [47] J. Moya, C.F. Bearer, R.A. Etzel, Children's behavior and physiology and how it affects exposure to environmental contaminants, Pediatrics 113 (Suppl) (2004) 996–1006.
- [48] I. Nam, J. Yang, D. Lee, E. Park, J. Sohn, A study on the thermal comfort and clothing insulation characteristics of preschool children in Korea, Build. Environ. 92 (2015) 724–733, <https://doi.org/10.1016/j.buildenv.2015.05.041>.
- [49] CIBSE Guide A, The Chartered Institution of Building Services Engineers, Environmental design, 2014.
- [50] CIBSE Guide B2, Ventilation and Ductwork, 2016.
- [51] S.S. Korsavi, A. Montazami, Adaptive behaviours and occupancy patterns in UK primary schools: impacts on comfort and indoor quality, in: Windsor Conference, Rethinking Comfort, 2018, pp. 627–639.
- [52] S.S. Korsavi, A. Montazami, Children's thermal comfort and adaptive behaviours; UK primary schools during non-heating and heating seasons, Energy Build. 214 (2020) 109857, <https://doi.org/10.1016/j.enbuild.2020.109857>.
- [53] Y. Wang, J. Kuckelkorn, F.Y. Zhao, D. Liu, A. Kirschbaum, J.L. Zhang, Evaluation on classroom thermal comfort and energy performance of passive school building by optimizing HVAC control systems, Build. Environ. 89 (2015) 86–106, <https://doi.org/10.1016/j.buildenv.2015.02.023>.
- [54] S. Haddad, P. Osmond, S. King, Revisiting thermal comfort models in Iranian classrooms during the warm season, Build. Res. Inf. 3218 (2016) 1–17, <https://doi.org/10.1080/09613218.2016.1140950>.
- [55] P. Wargocki, D.P. Wyon, Providing better thermal and air quality conditions in school classrooms would be cost-effective, Build. Environ. 59 (2013) 581–589, <https://doi.org/10.1016/j.buildenv.2012.10.007>.
- [56] D. Zhang, P.M. Bluyssen, Actions of primary school teachers to improve the indoor environmental quality of classrooms in The Netherlands, Intell. Build. Int. (2019) 1–13, <https://doi.org/10.1080/17508975.2019.1617100>, 0.
- [57] D.J. Clements-Croome, H.B. Awbi, Z. Bakó-Bíró, N. Kochhar, M. Williams, Ventilation rates in schools, Build. Environ. 43 (2008) 362–367, <https://doi.org/10.1016/j.buildenv.2006.03.018>.
- [58] M.C.C. Katafygiotou, D.K.K. Serghides, Indoor comfort and energy performance of buildings in relation to occupants' satisfaction: investigation in secondary schools of Cyprus, Adv. Build. Energy Res. 8 (2014) 216–240, <https://doi.org/10.1080/17512549.2013.865554>.
- [59] E.G. Dascalaki, V.G. Sermpetzoglou, Energy performance and indoor environmental quality in Hellenic schools, Energy Build. 43 (2011) 718–727, <https://doi.org/10.1016/j.enbuild.2010.11.017>.
- [60] L. Lan, P. Wargocki, D.P. Wyon, Z. Lian, Effects of thermal discomfort in an office on perceived air quality, SBS symptoms, physiological responses, and human performance, Indoor Air 21 (5) (2011) 376–390, <https://doi.org/10.1111/j.1600-0668.2011.00714.x>.
- [61] M. Kottek, J. Grieser, C. Beck, B. Rudolf, F. Rubel, World map of the Köppen-Geiger climate classification updated, Meteorol. Z. 15 (2006) 259–263.
- [62] E. Gratia, I. Bruyere, A. De Herde, How to use natural ventilation to cool narrow office buildings, Build. Environ. 39 (2004) 1157–1170.
- [63] D. Mumovic, O. Wilton, S.-M. Hong, Designing Natural Ventilation for Urban Buildings, Routledge, 2018.
- [64] G.J. Levermore, The exponential limit to the cooling of buildings by natural ventilation, Build. Serv. Eng. Technol. 32 (2) (2002) 119–125, <https://doi.org/10.1191/0143624402bt0320a>.
- [65] K. Roth, J. Dieckmann, J. Brodrick, Natural and hybrid ventilation, ASHRAE J. 48 (6) (2006) H37–H39.
- [66] D. Teli, P.A.B. James, M.F. Jentsch, D. Teli, P.A.B. James, M.F. Jentsch, P.A. B. James, M.F. Jentsch, School Classrooms Thermal Comfort in Naturally Ventilated Primary School Classrooms, 2013, p. 3218, <https://doi.org/10.1080/09613218.2013.773493>.
- [67] A. Montazami, M. Wilson, F. Nicol, Aircraft noise, overheating and poor air quality in classrooms in London primary schools, Build. Environ. Times 52 (2012) 129–141, <https://doi.org/10.1016/j.buildenv.2011.11.019>.
- [68] C. Allocca, Q. Chen, L.R. Glicksman, Design analysis of single-sided natural ventilation, Energy Build. 35 (2003) 785–795, [https://doi.org/10.1016/S0378-7788\(02\)00239-6](https://doi.org/10.1016/S0378-7788(02)00239-6).
- [69] CIBSE TM 21, Minimising pollution at air intakes, 1999.
- [70] CIBSE TM46, Energy benchmarks, 2008.
- [71] T.S. Larsen, P. Heiselberg, Single-sided natural ventilation driven by wind pressure and temperature difference, Energy Build. 40 (6) (2008) 1031–1040, <https://doi.org/10.1016/j.enbuild.2006.07.012>.
- [72] Y. Hou, J. Liu, J. Li, Investigation of indoor air quality in primary school classrooms, Procedia Eng 121 (2015) 830–837, <https://doi.org/10.1016/j.proeng.2015.09.037>.
- [73] L. Stabile, M. Dell'Isola, A. Frattolillo, A. Massimo, A. Russi, Effect of natural ventilation and manual airing on indoor air quality in naturally ventilated Italian classrooms, Build. Environ. 98 (2016) 180–189, <https://doi.org/10.1016/j.buildenv.2016.01.009>.
- [74] S.A. Ghita, T. Catalina, Energy efficiency versus indoor environmental quality in different Romanian countryside schools, Energy Build. 92 (2015) 140–154, <https://doi.org/10.1016/j.enbuild.2015.01.049>.
- [75] T. Moore, D. Carter, A. Slater, User attitudes toward occupant controlled office lighting, Light. Res. Technol. 34 (2002) 207–219, <https://doi.org/10.1191/1365782802lt0480a>.
- [76] V. Inkarojrit, Monitoring and modelling of manually-controlled Venetian blinds in private offices: a pilot study, J. Build. Perform. Simul. 1 (2008) 75–89, <https://doi.org/10.1080/19401490802021012>.
- [77] H.B. Rijal, P.G. Tuohy, J.F. Nicol, M.A. Humphreys, A.a. Samuel, J.a. Clarke, Development of an adaptive window-opening algorithm to predict the thermal comfort, energy use and overheating in buildings, J. Build. Eng. 1 (2008) 17–30, <https://doi.org/10.1080/19401490701868448>.
- [78] Y. Zhang, P. Barrett, Factors influencing the occupants' window opening behaviour in a naturally ventilated office building, Build. Environ. 50 (2012) 125–134, <https://doi.org/10.1016/j.buildenv.2011.10.018>.
- [79] B. Meerbeek, M. te Kulve, T. Gritti, M. Aarts, E. van Loenen, E. Aarts, Building automation and perceived control: a field study on motorized exterior blinds in Dutch offices, Build. Environ. 79 (2014) 66–77, <https://doi.org/10.1016/j.buildenv.2014.04.023>.
- [80] S.A. Sadeghi, P. Karava, I. Konstantzos, A. Tzempelikos, Occupant interactions with shading and lighting systems using different control interfaces: a pilot field study, Build. Environ. 97 (2016) 177–195, <https://doi.org/10.1016/j.buildenv.2015.12.008>.
- [81] G. Iwashita, H. Akasaka, "The effects of human behavior on natural ventilation rate and indoor air environment in summer—a field study in southern Japan, Energy Build. 25 (3) (1997) 195–205.
- [82] G. Bekö, J. Toftum, G. Clausen, Modeling ventilation rates in bedrooms based on building characteristics and occupant behavior, Build. Environ. 46 (2011) 2230–2237, <https://doi.org/10.1016/j.buildenv.2011.05.002>.
- [83] M.A.A. Humphreys, A study of the thermal comfort of primary school children in summer, Build. Environ. 12 (1977) 231–239, [https://doi.org/10.1016/0360-1323\(77\)90025-7](https://doi.org/10.1016/0360-1323(77)90025-7).
- [84] S.S. Korsavi, A. Montazami, Developing a valid method to study adaptive behaviours with regard to IEQ in primary schools, Build. Environ. Times 153 (2019) 1–16, <https://doi.org/10.1016/j.buildenv.2019.02.018>.
- [85] M. Olawale, K. Alkhaja, M. Bin Sulayem, B. Abu-hijleh, Evaluation of indoor environmental quality conditions in elementary schools' classrooms in the United Arab Emirates, Front. Archit. Res. 3 (2014) 166–177, <https://doi.org/10.1016/j.foar.2014.03.001>.
- [86] ISO Standard 7726, Ergonomics of the Thermal Environment — Instruments for Measuring Physical Quantities, International Organization for Standardization, Geneva, 2001.
- [87] ISO Standard 7730, Ergonomics of the thermal environment Analytical determination and interpretation of thermal comfort using calculation of the PMV and PPD indices and local thermal comfort criteria, International Organization for Standardization, Geneva (2005).
- [88] P. Ajiboye, M. White, H. Graves, D. Ross, Ventilation and Indoor Air Quality in Schools: Guidance Report 202825: Building Research Technical Report 20/2005, 2006.
- [89] S. Kamaruzzaman, R. Razak, Measuring indoor air quality performance in Malaysian government kindergarden, J. Build. Perform. 2 (2011) 70–79.
- [90] S. Batterman, Review and extension of CO2-based methods to determine ventilation rates with application to school classrooms, Int. J. Environ. Res. Publ. Health 14 (2017), <https://doi.org/10.3390/ijerph14020145>.
- [91] CEN, EN 13779, Ventilation for Non-residential Buildings – Performance Requirements for Ventilation and Room- Conditioning Systems, European Committee for Standardization, 2007.
- [92] ASHRAE 2106, Ventilation for acceptable indoor air quality. ANSI/ ASHRAE Standard 62.1. (2016).
- [93] E. McCrum-gardner, Which is the correct statistical test to use? Br. J. Oral Maxillofac. Surg. 46 (1) (2008) 38–41, <https://doi.org/10.1016/j.bjoms.2007.09.002>.
- [94] A. Bryman, D. Cramer, Quantitative Data Analysis with IBM SPSS, vol. 17, Routledge, 2011, pp. 18–19.
- [95] A. Bryman, D. Cramer, Quantitative Data Analysis with SPSS 12 and 13: A Guide for Social Scientists, Psychology Press, 2005.
- [96] E. Marshall, E. Boggis, The statistics tutor's quick guide to commonly used statistical tests, Statstutor Community Proj (2016) 1–57.
- [97] Y.H. Chan, Biostatistics 102: quantitative data—parametric & non-parametric tests, Singap. Med. J. 44 (2003) 391–396.
- [98] J. Cohen, Statistical Power Analysis for the Behavioral Sciences, Academic press, 2013, <https://doi.org/10.4324/9780203771587>.
- [99] J.D. Evans, Straightforward Statistics for the Behavioral Sciences, Thomson Brooks/Cole Publishing Co., 1996.
- [100] A. Field, Discovering Statistics Using IBM SPSS Statistics, Sage Publications, 2013.
- [101] IBM Corp, IBM SPSS statistics for windows, version 24.0., Armonk, NY, USA, 2016.
- [102] D. Mumovic, M. Davies, I. Ridley, T. Oreszczyn, A methodology for post-occupancy evaluation of ventilation rates in school, Build. Serv. Eng. Technol. 2 (2009) 143–152, <https://doi.org/10.1177/0143624408099175>.
- [103] O. Ramalho, C. Mandin, J. Ribéron, G. Wyart, Air stiffness and air exchange rate in French schools and day-care centres, Int. J. Vent. 12 (2013) 175–180.
- [104] B.R. Barnes, Behavioural change, indoor air pollution and child respiratory health in developing countries: a review, J. Environ. Res. Public Heal. 11 (5) (2014) 4607–4618, <https://doi.org/10.3390/ijerph110504607>.
- [105] D. Teli, M.F. Jentsch, P.A.B. James, Naturally ventilated classrooms: an assessment of existing comfort models for predicting the thermal sensation and

- preference of primary school children, *Energy Build.* 53 (2012) 166–182, <https://doi.org/10.1016/j.enbuild.2012.06.022>.
- [106] A. Michael, J.F. Nicol, M.A. Humphreys, Understanding the adaptive approach to thermal comfort, *ASHRAE Trans* 104 (1998) 991–1004.
- [107] J. Kim, R. de Dear, Thermal comfort expectations and adaptive behavioural characteristics of primary and secondary school students, *Build. Environ.* 127 (2018) 13–22.
- [108] S. Dutton, L. Shao, Window opening behaviour in a naturally ventilated school, *Proc. SimBuild.* 4 (1) (2010) 260–268.
- [109] V. Fabi, R.V. Andersen, S. Corgnati, B.W. Olesen, Occupants' window opening behaviour: a literature review of factors influencing occupant behaviour and models, *Build. Environ.* 58 (2012) 188–198, <https://doi.org/10.1016/j.buildenv.2012.07.009>.
- [110] D. Wyon, P. Wargocki, J. Toftum, G. Clausen, Classroom ventilation must be improved for better health and learning, *REHVA. Eur. HVAC. J.* 3 (2010) 12–16, 2010.
- [111] L. Gunnarsen, P. Ole Fanger, P.O. Fanger, Adaptation to indoor air pollution, *Environ. Int.* 18 (1) (1992) 43–54.
- [112] L. Chatzidiakou, D. Mumovic, A.J. Summerfield, What do we know about indoor air quality in school classrooms? A critical review of the literature, *Intell. Build. Int.* 4 (2012) 228–259, <https://doi.org/10.1080/17508975.2012.725530>.
- [113] M. Griffiths, M. Eftekhari, Control of CO₂ in a naturally ventilated classroom, *Energy Build.* 40 (2008) 556–560, <https://doi.org/10.1016/j.enbuild.2007.04.013>.
- [114] P. Wargocki, N.A.F. Da Silva, Use of visual CO₂ feedback as a retrofit solution for improving classroom air quality, *Indoor Air* 25 (2015) 105–114, <https://doi.org/10.1111/ina.12119>.
- [115] L.M.J. Geelen, M.A.J. Huijbregts, A.M.J. Ragas, R.W. Bretveld, H.W.A. Jans, W. J. Van Doorn, S.J.C.J. Evertz, A. Van Der Zijden, Comparing the effectiveness of interventions to improve ventilation behavior in primary schools, *Indoor Air* 18 (2008) 416–424, <https://doi.org/10.1111/j.1600-0668.2008.00542.x>.
- [116] B. Cao, Q. Ouyang, Y. Zhu, L. Huang, H. Hu, G. Deng, Development of a multivariate regression model for overall satisfaction in public buildings based on field studies in Beijing and Shanghai, *Build. Environ. Times* 47 (2012) 394–399, <https://doi.org/10.1016/j.buildenv.2011.06.022>.
- [117] K.H. Bartlett, M. Martinez, J. Bert, Modeling of occupant-generated CO₂ dynamics in naturally ventilated classrooms, *J. Occup. Environ. Hyg.* 1 (3) (2004) 139–148, <https://doi.org/10.1080/15459620490424393>.
- [118] A.B. Lugg, W.J. Batty, Air quality and ventilation rates in school classrooms I: air quality monitoring, *Build. Serv. Eng. Technol.* 20 (1999) 13–21.
- [119] E. Chatzidiakou, D. Mumovic, A.J. Summerfield, H.M. Altamirano, Indoor air quality in London schools. Part 1: 'performance in use', *Intell. Build. Int.* 7 (2–3) (2015) 101–129, <https://doi.org/10.1080/17508975.2014.918870>.
- [120] C.A. Mydlarz, R. Conetta, D. Connolly, T.J. Cox, J.E. Dockrell, B.M. Shield, Comparison of environmental and acoustic factors in occupied school classrooms for 11–16 year old students, *Build. Environ. Times* 60 (2013) 265–271, <https://doi.org/10.1016/j.buildenv.2012.10.020>.
- [121] Eurostat, School enrolment and levels of education, 2011.
- [122] DfES (Department for Education and Skills), *Building Bulletin 99: Briefing Framework for Primary School Projects*, 2006.
- [123] A. Montazami, M. Gaterell, F. Nicol, A comprehensive review of environmental design in UK schools: history, conflicts and solutions, *Renew. Sustain. Energy Rev.* 46 (2015) 249–264, <https://doi.org/10.1016/j.rser.2015.02.012>.
- [124] A. Abend, E.B. Sheila Walbe Ornstein, J. de la Garza, C. Watson, K. Lange, H. von Ahlefeld, Evaluating quality in educational facilities, *PEB Exch. Program. Educ. Build. OECD Publi* (2006), <https://doi.org/10.1787/530661814151>.
- [125] T. Moja, Nigeria education sector analysis: an analytical synthesis of performance and main issues, *World Bank Report* 3 (2000).